Convective processes,
Clouds in the climate system,
and their Spatial organization

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Theoretical Advances in Planetary Flows and Climate Dynamics
Les Houches, March 2015

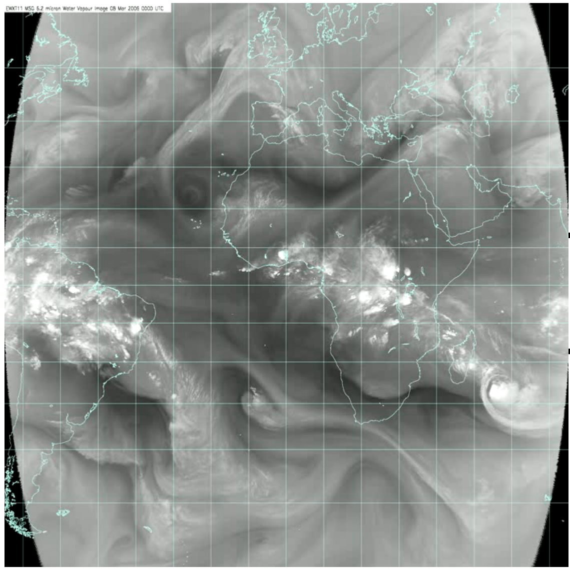
Outline

- Clouds in the climate system

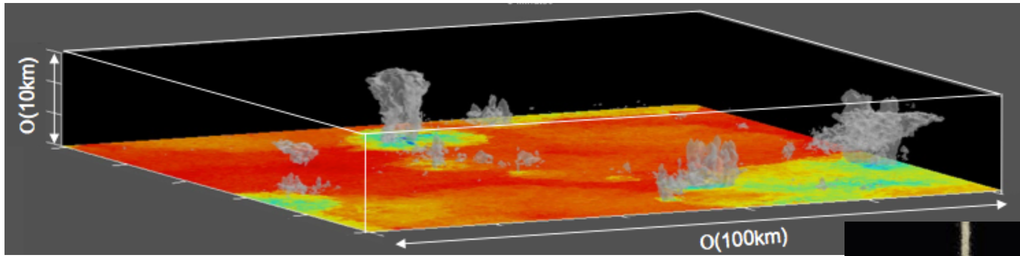
- Spatial distribution of tropical deep convection

Radiative-convective equilibrium
Clouds over surface temperature

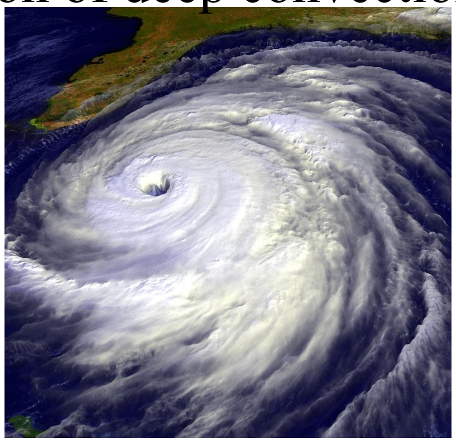
Water vapor from satellite



Tropical « pop corn » convection



- Spontaneous organization of deep convection



[Raymond, Zeng QJRMS 2000;
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Clouds in the climate system

Courtesy John Taylor
Fluid Dynamics of Sustainability and the Environment

"How inappropriate to call this planet Earth, when clearly it is Ocean." - Arthur C. Clark

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and clouds

Clouds in the climate system

Cumulus: heap, pile

Stratus: flatten out, cover with a layer

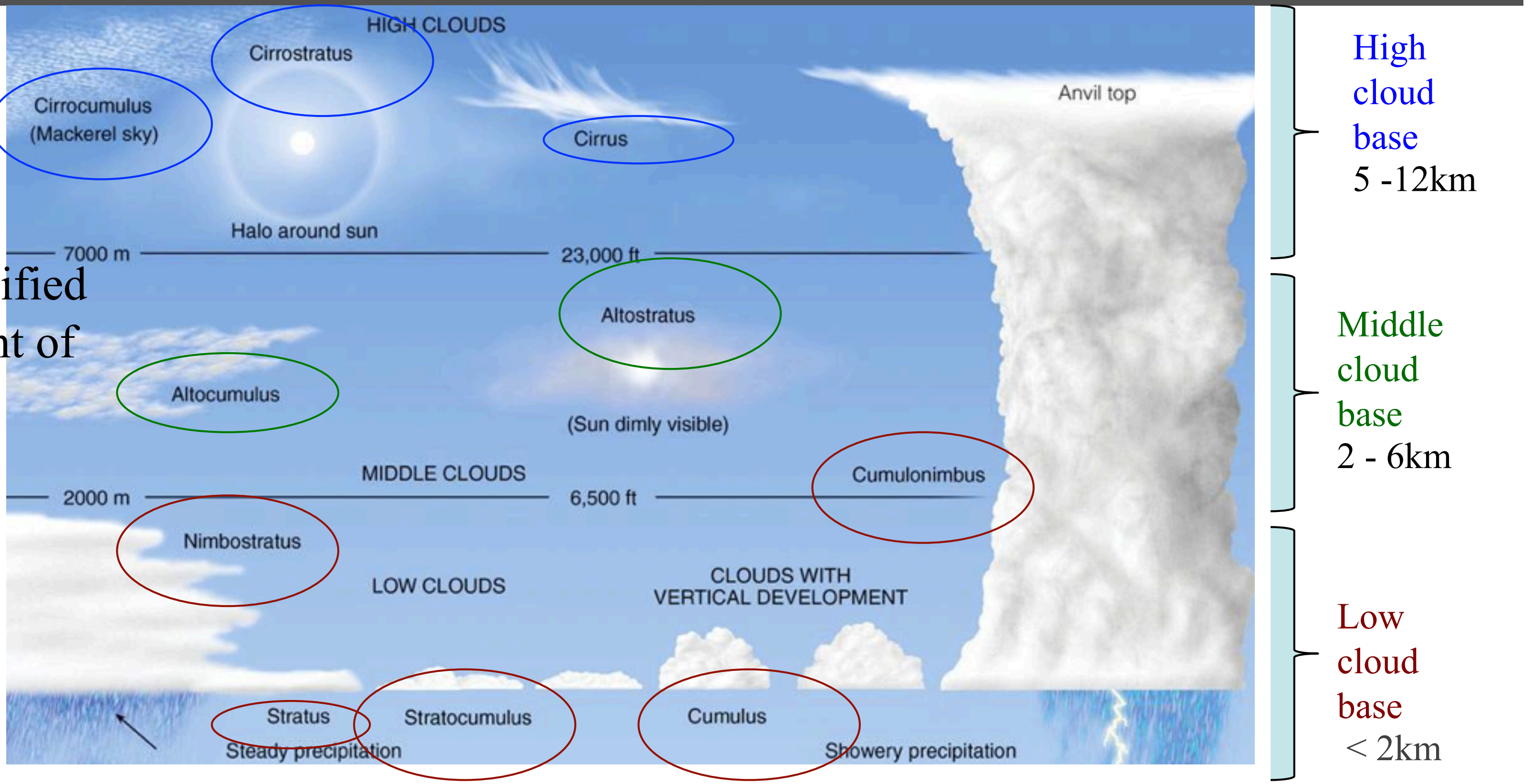
Cirrus: lock of hair, tuft of horsehair

Nimbus: precipitating cloud

Altum: height

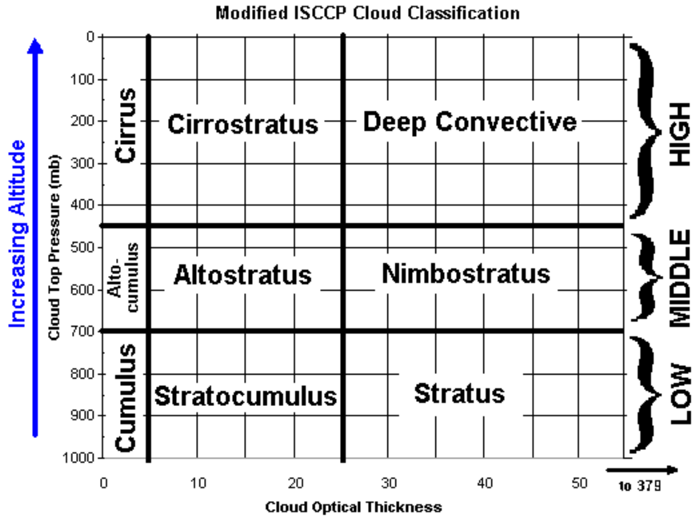
Combined to define 10 cloud types

Clouds in the climate system



Clouds were classified according to height of cloud base and appearance

ISCCP cloud classification



Classified according to cloud top pressure

Clouds in the climate system

Cirrostratus

Cirrus

Cirrocumulus

Clouds in the climate system

Altocumulus

Altostratus

Clouds in the climate system

Stratocumulus

Cumulonimbus

Stratus

Cumulus

Nimbostratus

Clouds in the climate system

Other spectacular Clouds…

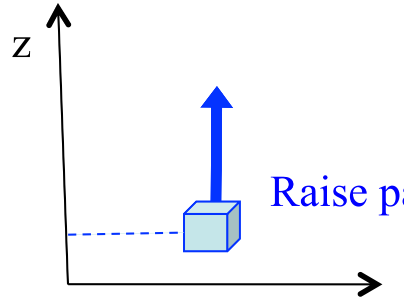
Mammatus clouds (typically below anvil clouds)

Shelf clouds (gust front)

Lenticular clouds (over orography)

Clouds in the climate system

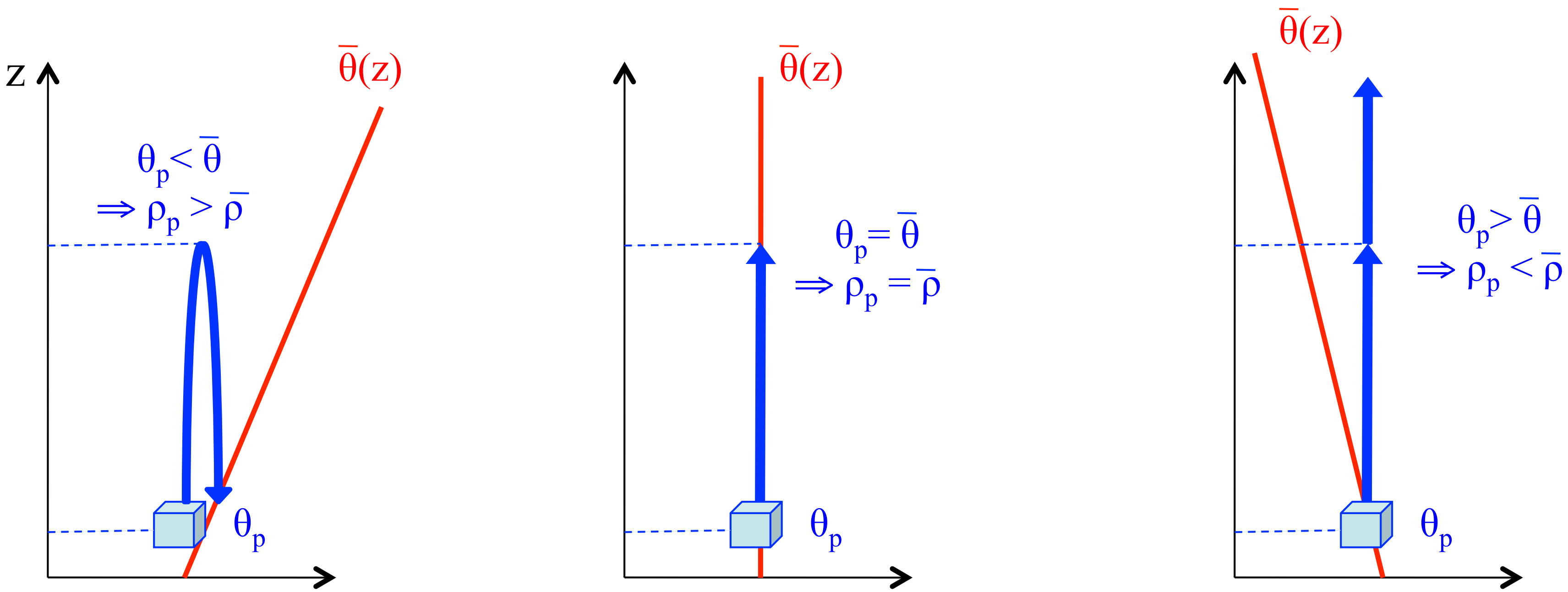
When is an atmosphere unstable to dry convection? => parcel method



Raise parcel adiabatically. Comes back to initial position?

(Potential temperature $\theta = T\,(p_0\,/\,p)^{R/cp}$ conserved under adiabatic displacements)

[Emanuel 94]



STABLE NEUTRAL UNSTABLE

When potential temperature $\theta = T\,(p_0\,/\,p)^{R/cp}$ decreases with height

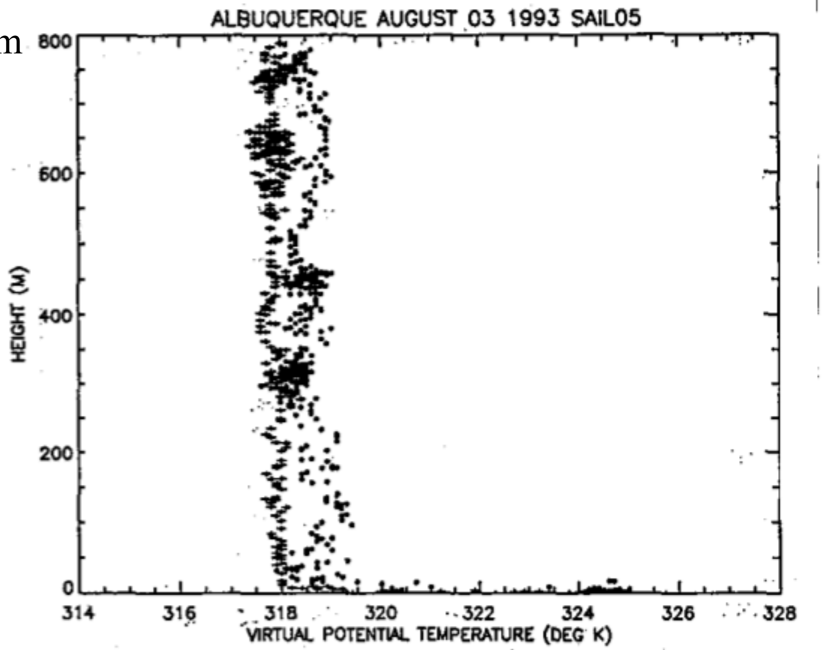
Clouds in the climate system

Convective adjustment time scales is very fast (minutes for dry convection) compared to destabilizing factors (surface warming, atmospheric radiative cooling…)

=> The observed state is very close to convective neutrality

Dry convective boundary layer over daytime desert

<1km



[Renno and Williams, 1995]

But above a thin boundary layer, not true anymore that θ = constant. Why?…

Clouds in the climate system

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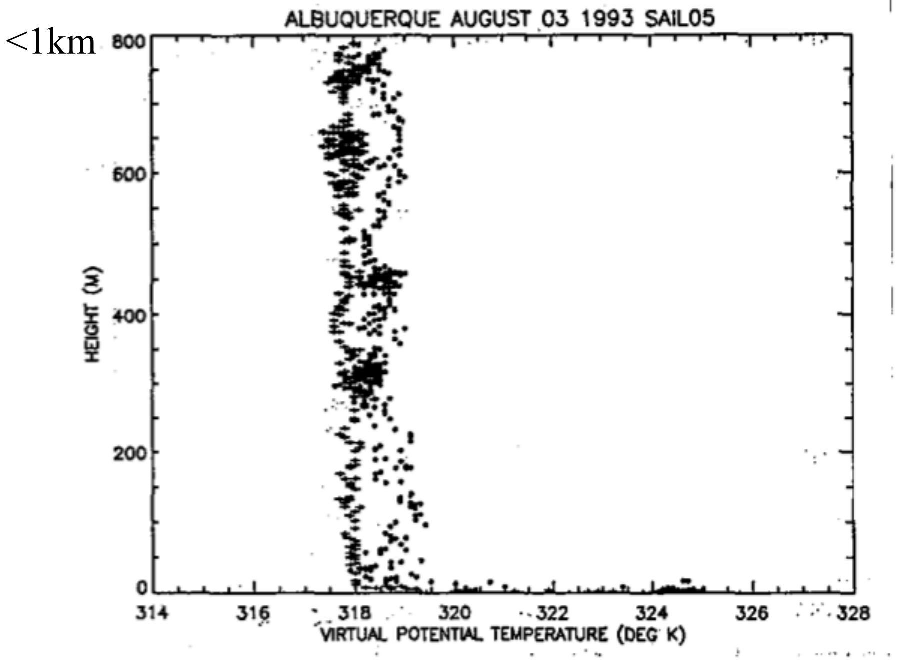


[Renno and Williams, 1995]

But above a thin boundary layer, not true anymore that θ = constant. Why?…

Most atmospheric convection involves phase change of water
Significant latent heat with phase changes of water = Moist Convection

Equivalent potential temperature $\theta_e = T\,(p_0 / p)^{R/cp}\; e^{\,Lv\, qv / (cp\, T)}$ is (approximately) conserved under adiabatic displacements

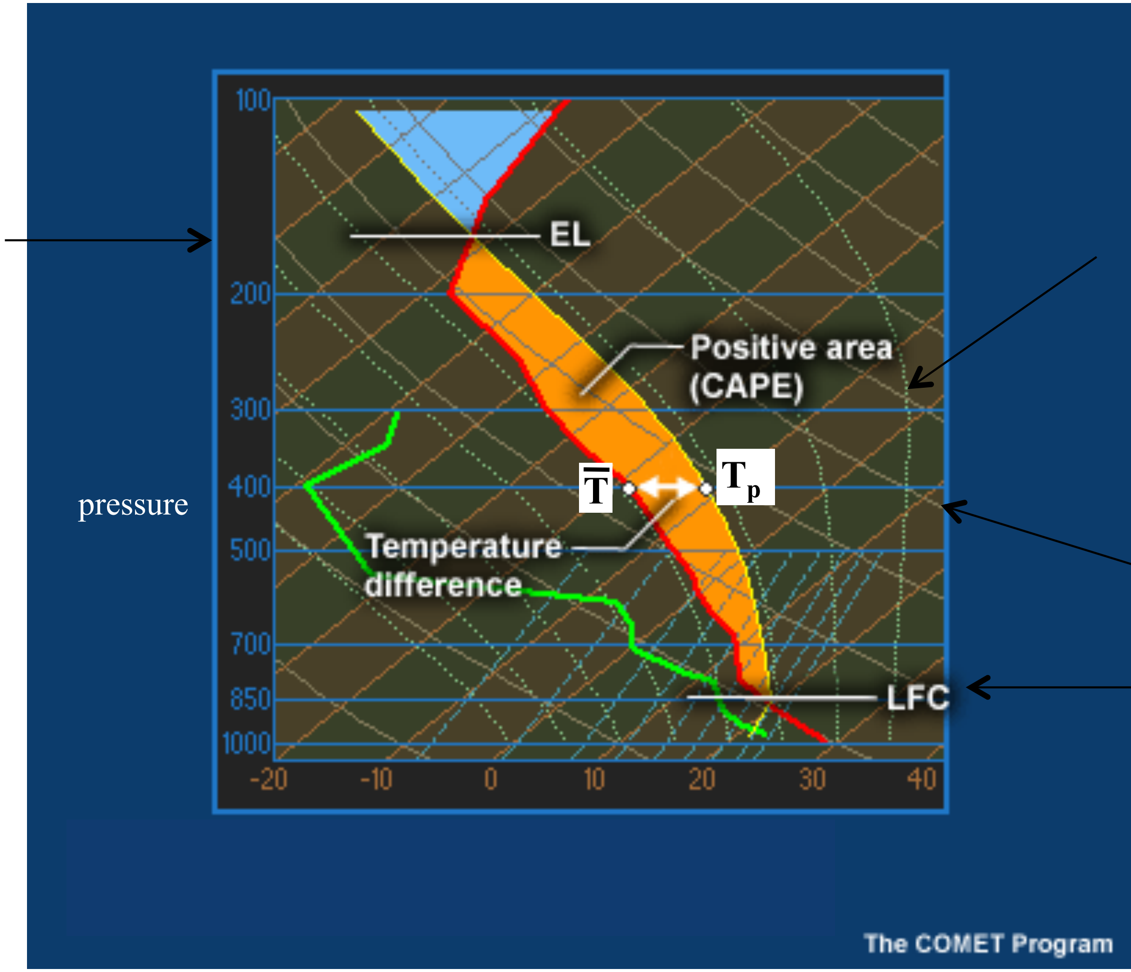
[Emanuel 94]

Clouds in the climate system

When is an atmosphere unstable to moist convection ?

Skew T diagram (isoT slanted), atmospheric T in red

EL equilibrium level



Moist adiabat θ_e= cstt

Dry adiabat θ = cstt

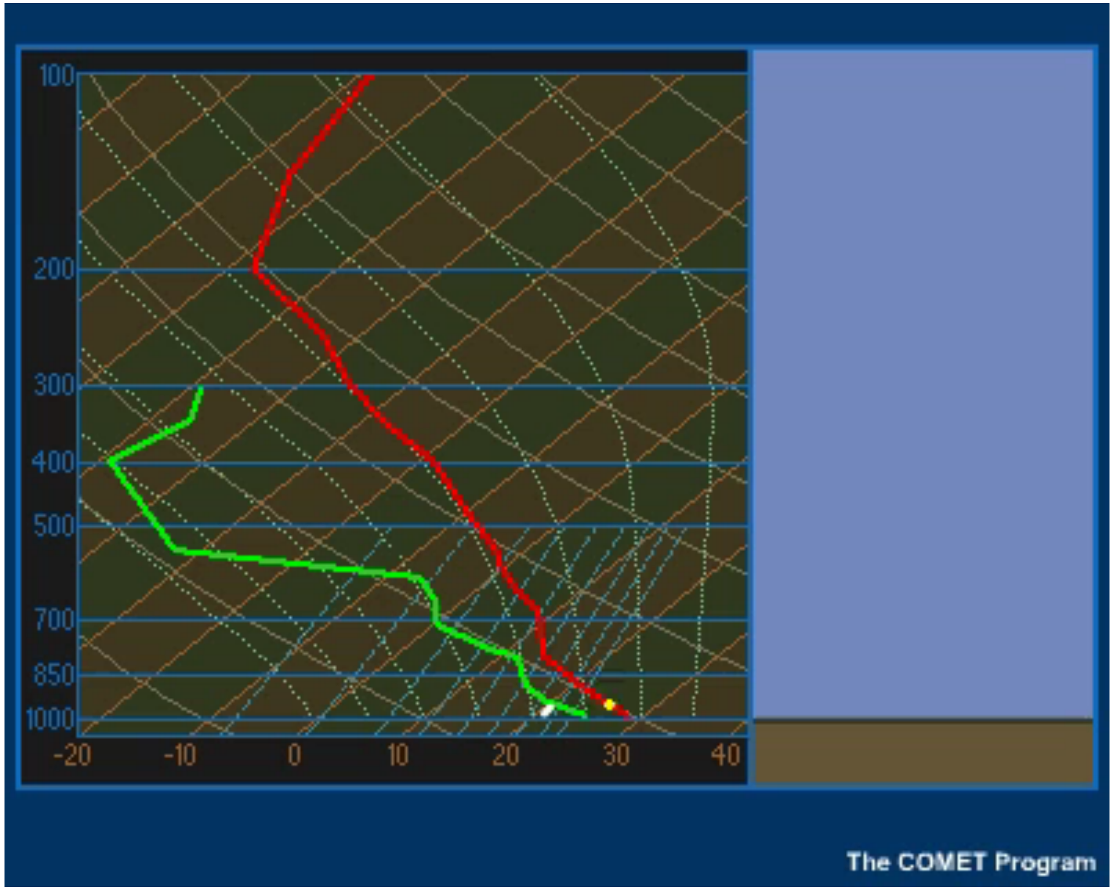
LFC level of free convection (= LCL lifted condensation level for simplicity)

CAPE: convective available potential energy

Moist convection

Parcel = yellow dot

EL equilibrium level



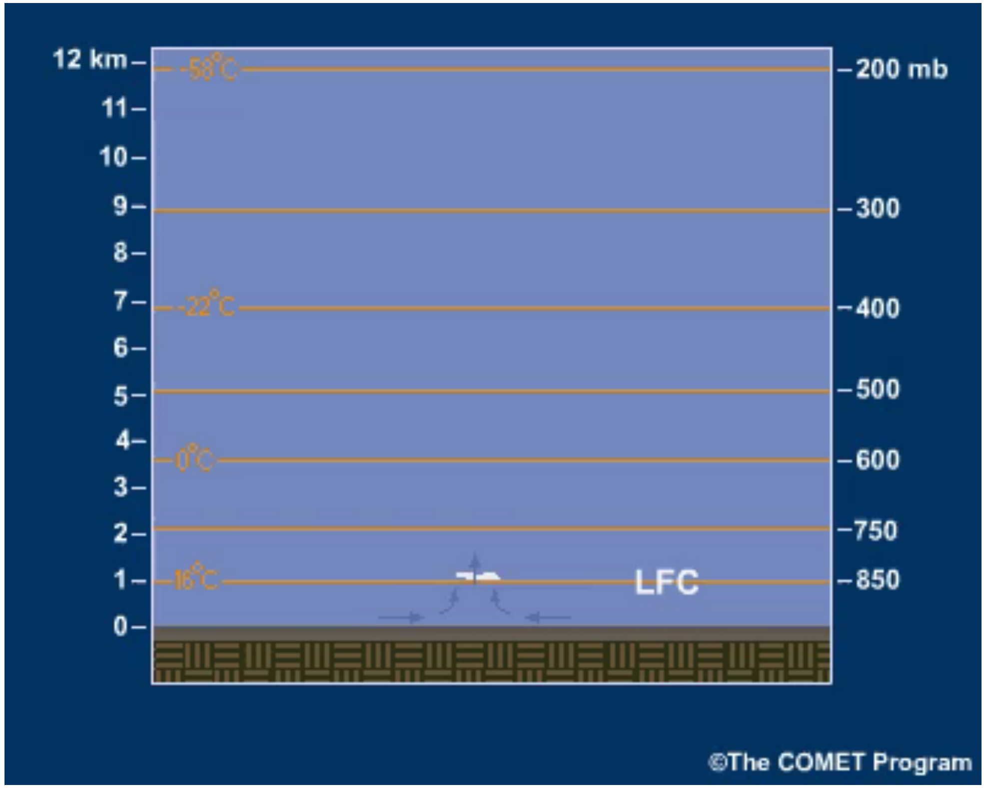
LFC level of free convection

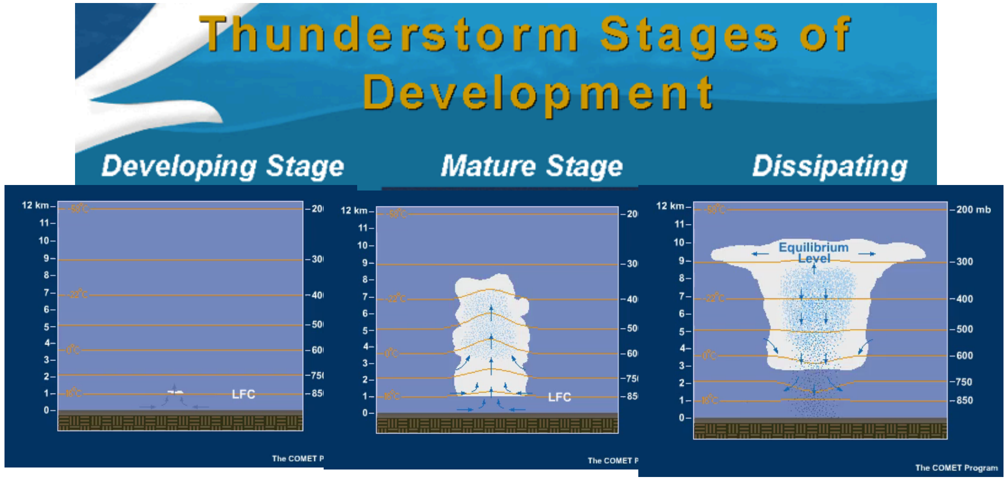
CAPE: convective available potential energy

Clouds in the climate system

If enough atmospheric instability present, cumulus clouds are capable of producing serious storms!!!

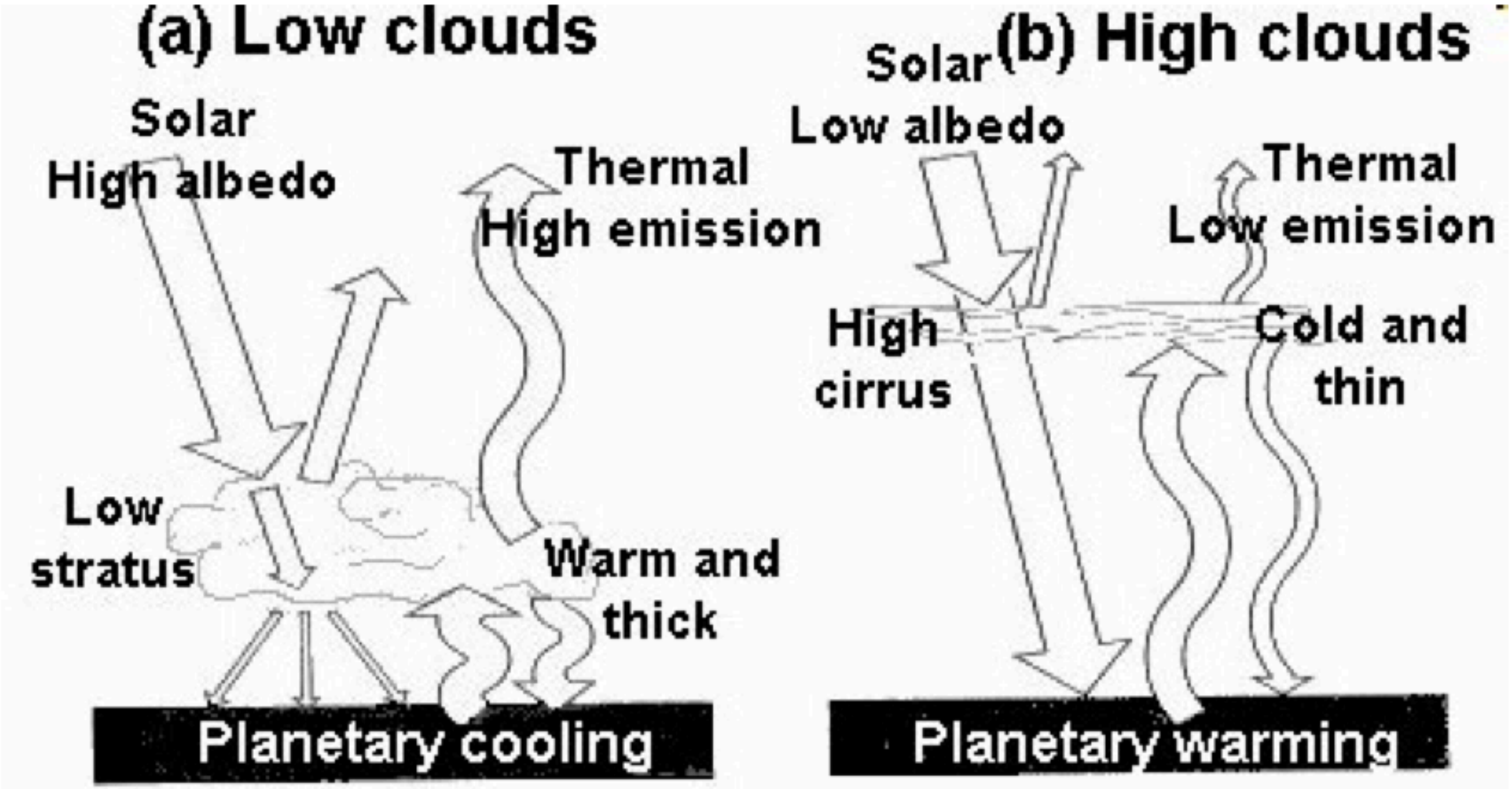
Strong updrafts develop in the cumulus cloud => mature, deep cumulonimbus cloud.
Associated with heavy rain, lightning and thunder.





Evaporative driven cold pools

Clouds in the climate system



More low clouds:

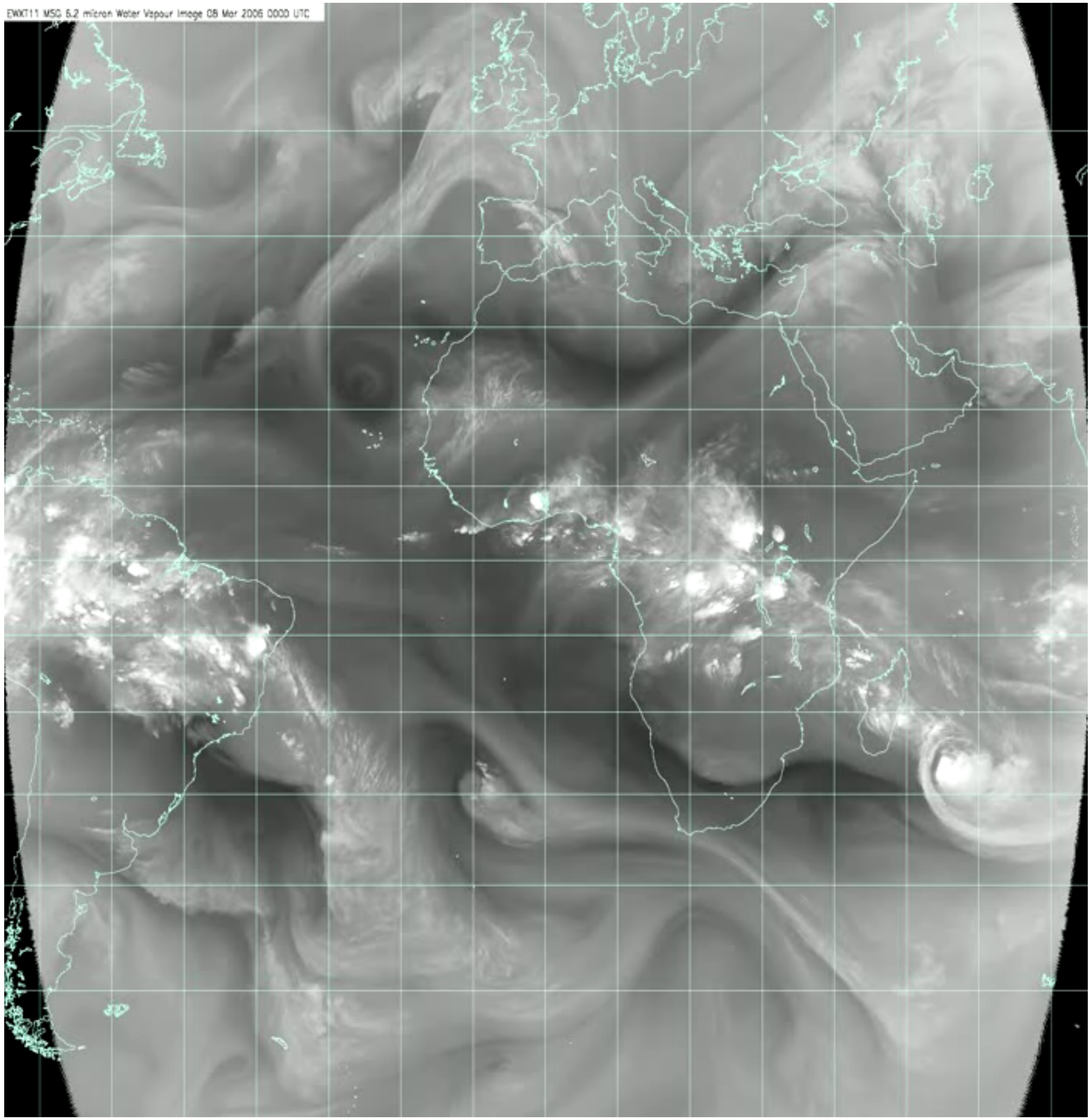
- Little LW effect ($\sim\sigma T^4$, T~Tsfc)
- Strong SW cooling

More high clouds:

- Strong LW warming ($\sim\sigma T^4$, T<<Tsfc)
- Little SW effect

Clouds in the climate system

Water vapor from satellite



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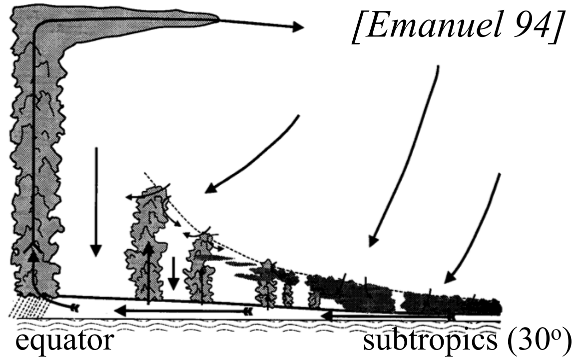
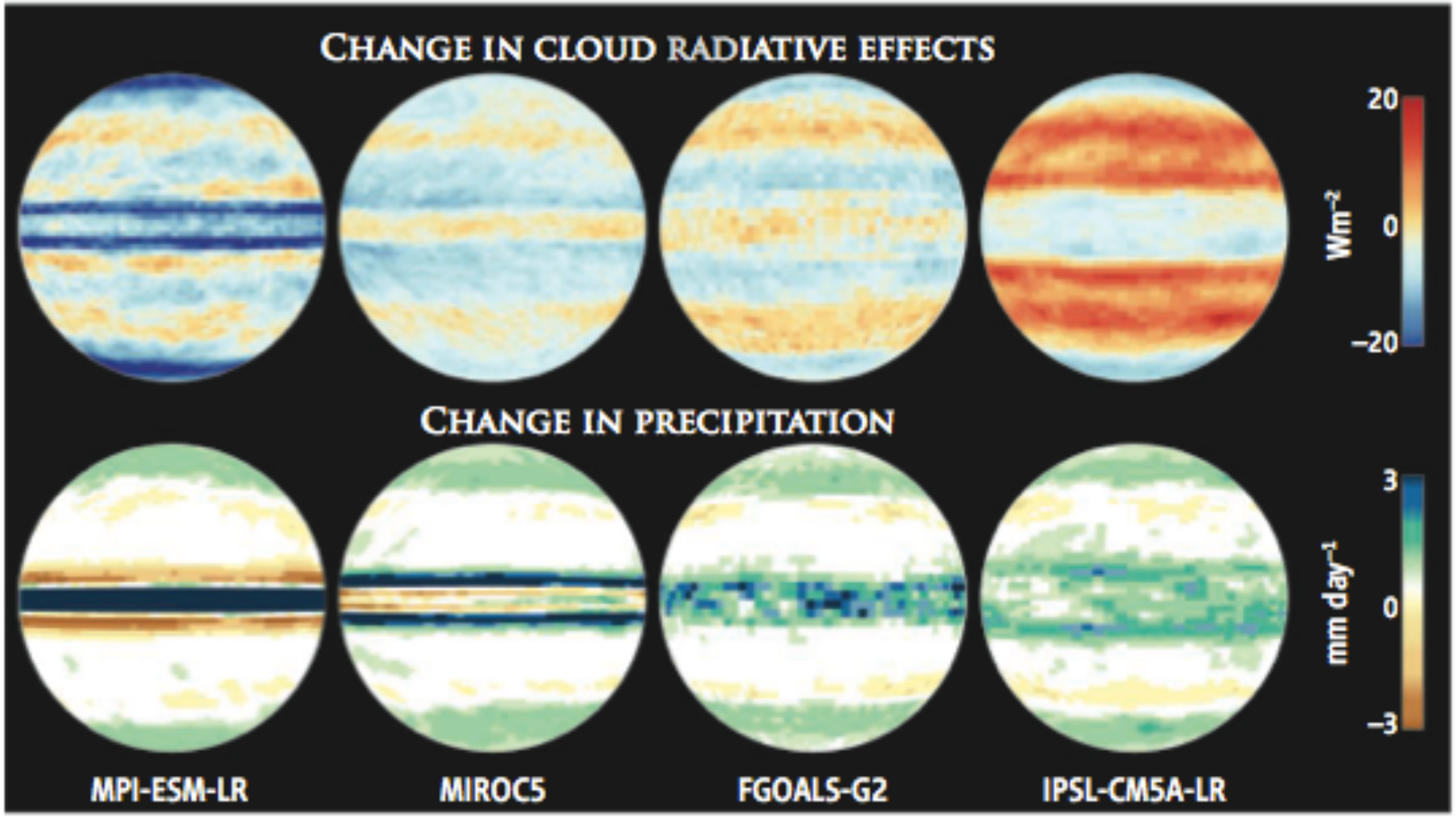


Small-scale tropical convection ⇒ parameterized in global climate models

Uncertainties in convective parameterizations …

Clouds in the climate system

Uncertainties in convective parameterizations



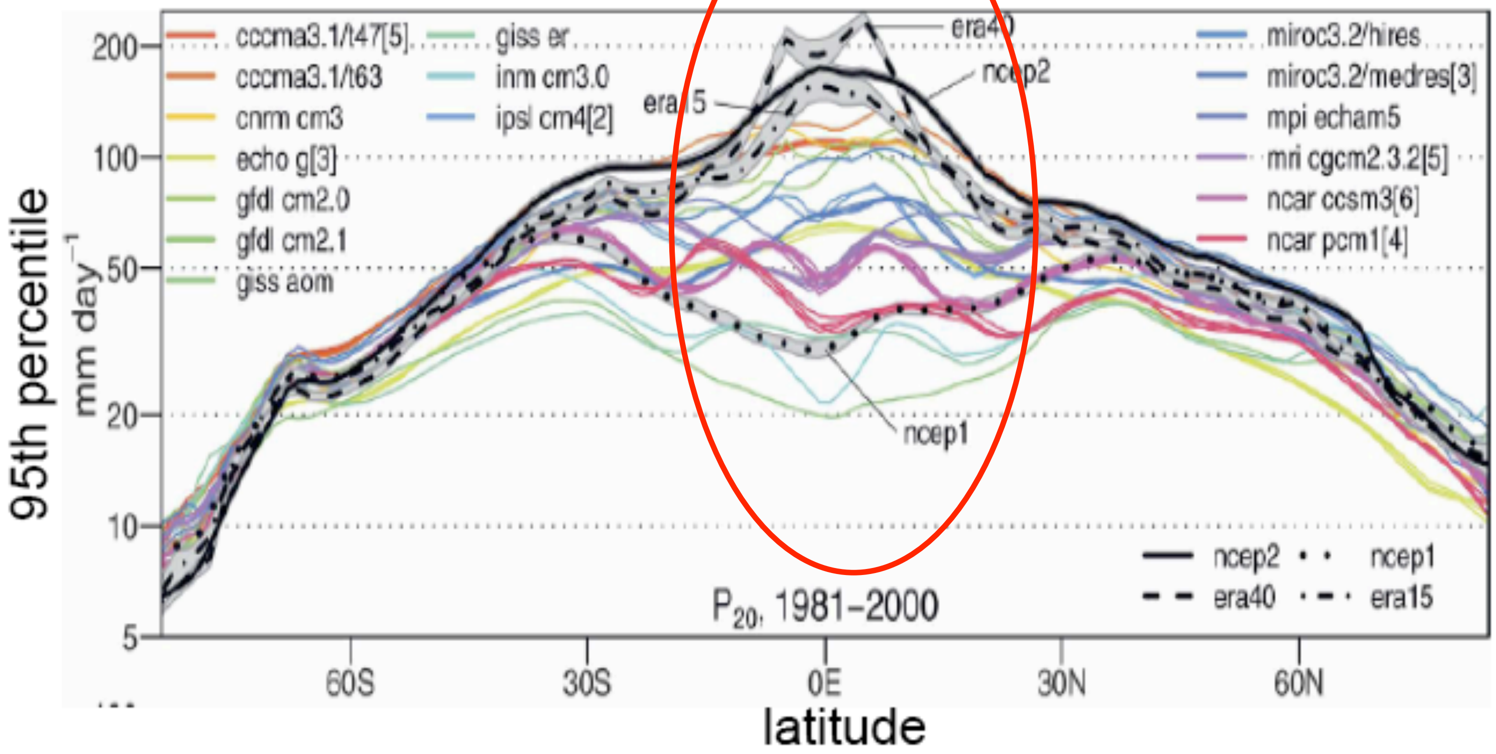
Wide variation. The response patterns of clouds and precipitation to warming vary dramatically depending on the climate model, even in the simplest model configuration. Shown are changes in the radiative effects of clouds and in precipitation accompanying a uniform warming (4°C) predicted by four models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a water planet with prescribed surface temperatures.

[Stevens & Bony, Science 2013]

Clouds in the climate system

Uncertainties in convective parameterizations

Precip extremes (95th percentile) in climate models and reanalysis



⇒Values NOT consistent in tropics and subtropics *[Kharin et al, 06]*

⇒Not correlated with resolution, hence convection param

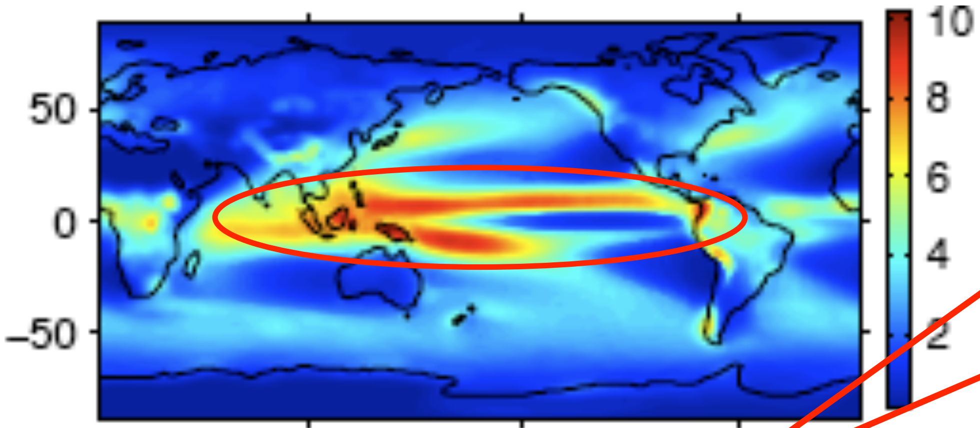
⇒Models disagree *[O'Gorman&Schneider, 09; Sugiyama,Shiogama,Emori, 10]*

Clouds in the climate system

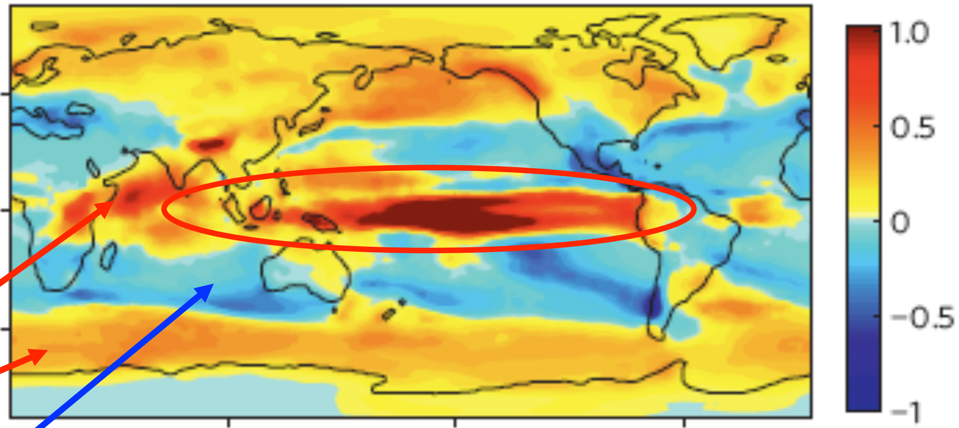
Robust responses between models

[Held & Soden, J. Clim., 2006]
1200+ citations

P (mm/day)
1981-1999 climatology



dP (mm/day)
(2081-2099) minus (1981-1999)



Increase in Tropics & Extratropics

Decrease in Subtropics

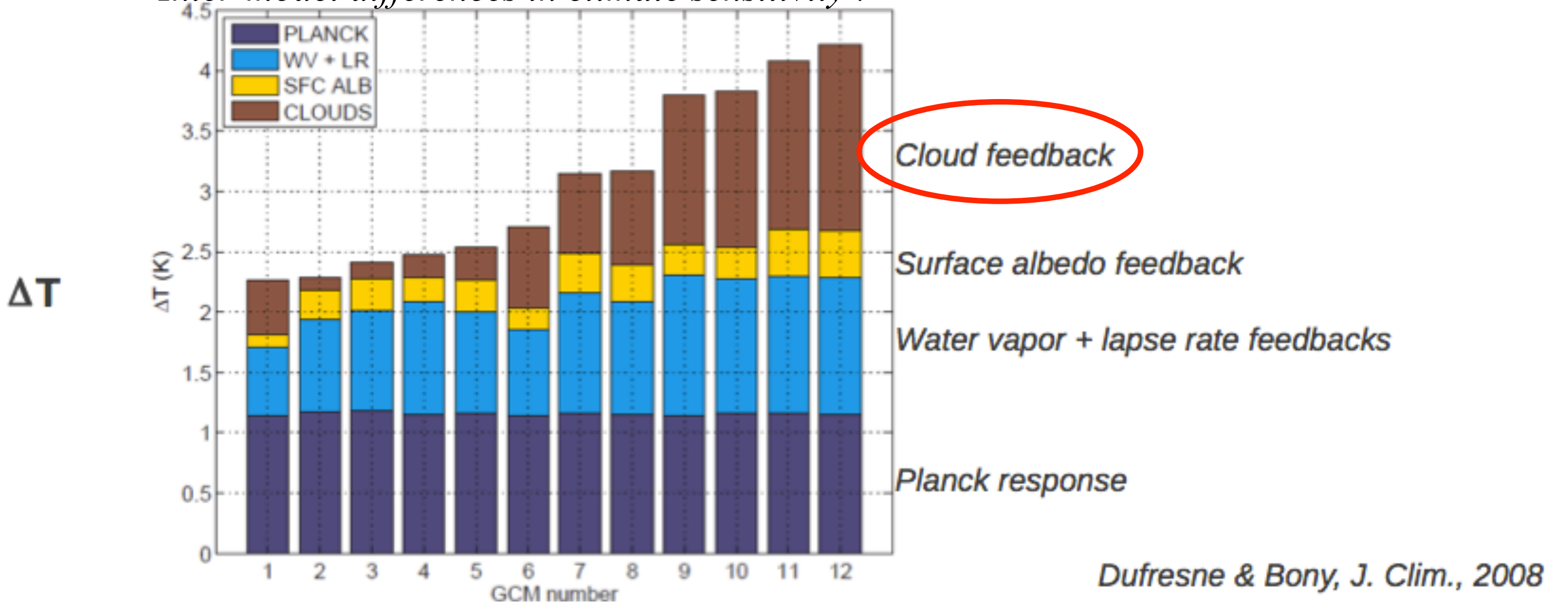
Warming => "Rich get richer"

[Chou & Neelin, J. Clim., 2004
Muller & O'Gorman, Nat. Clim. Change, 2011]

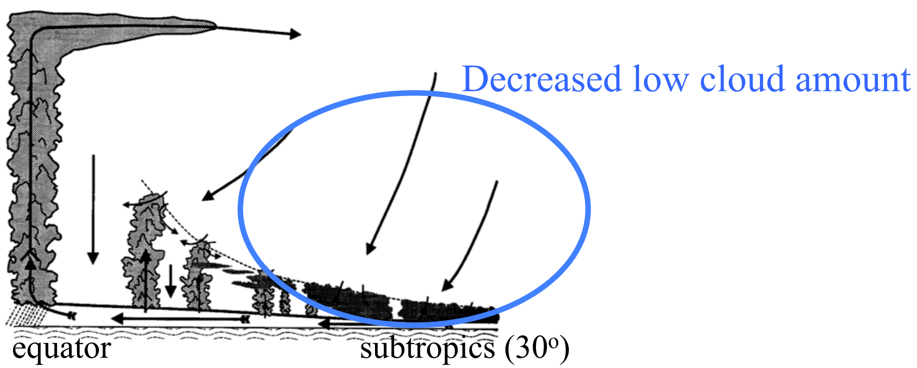
Clouds in the climate system

Climate sensitivity: equilibrium change in global mean surface temperature ΔT_s when atmospheric CO_2 is doubled.

Inter-model differences in climate sensitivity :



Uncertainty partly due to decreased low cloud amount



Zelinka et al., J. Climate, 2013

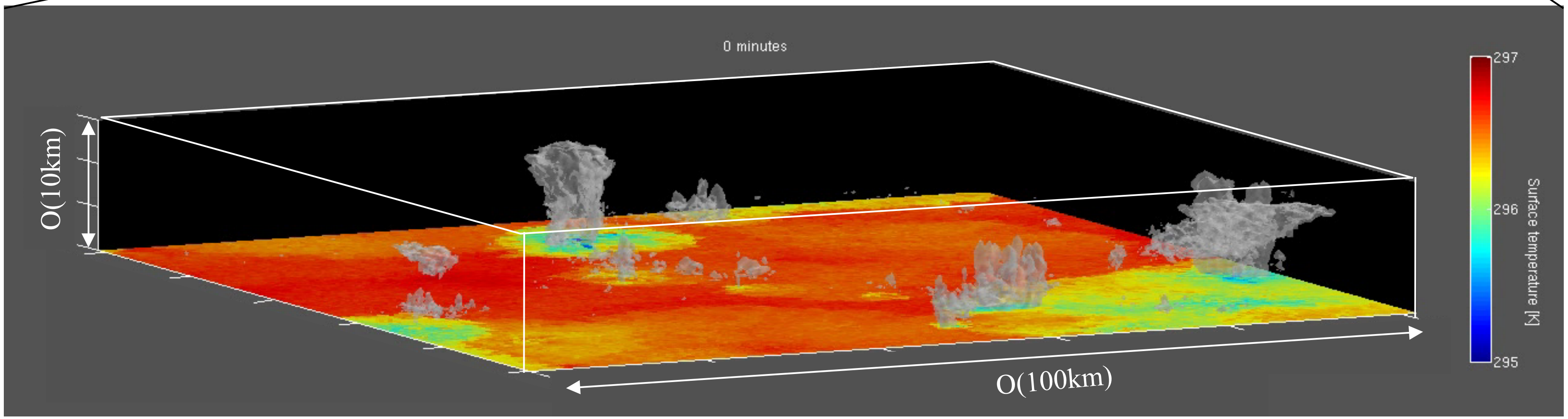
Clouds in the climate system

Grid of Global Climate Model

Question of interest:

What is the spatial distribution of deep convective clouds?

Clouds (gray surfaces) over near-surface temperature (colors)



Clouds in the climate system

SUMMARY PART 1: CLOUDS IN THE CLIMATE SYSTEM:

⇒ Clouds are one of the largest sources of uncertainty in climate predictions

⇒ Radiative impact important, both in longwave and shortwave
Affect atmospheric energy budget

⇒ Uncertainty from :
Change in low cloud cover
Convective parameterizations of deep clouds

Outline

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• Spatial distribution of tropical deep convection

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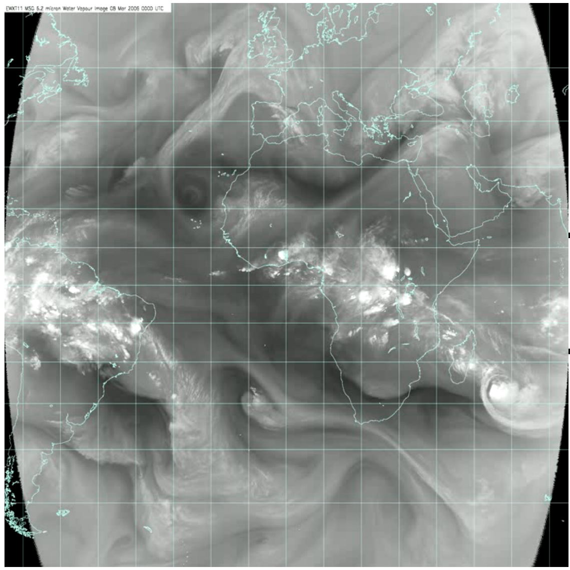
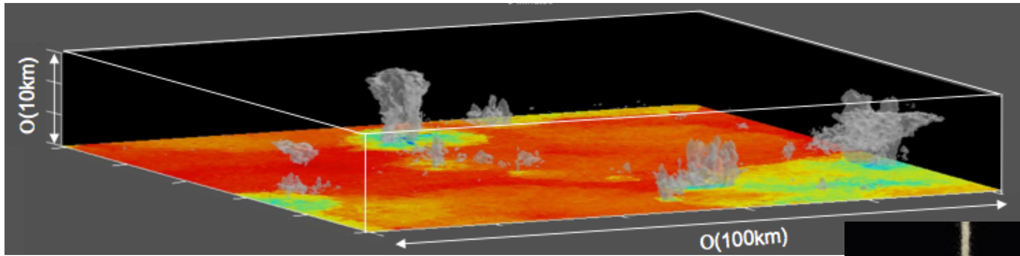
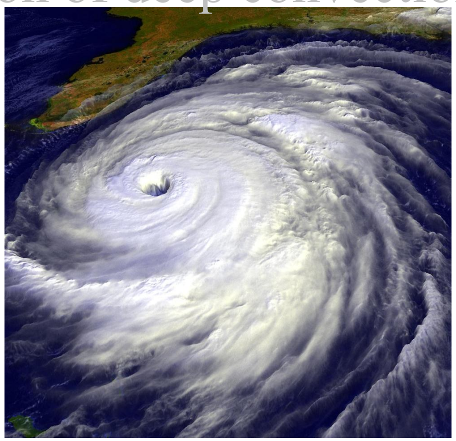




Tropical « pop corn » convection

• Spontaneous organization of deep convection



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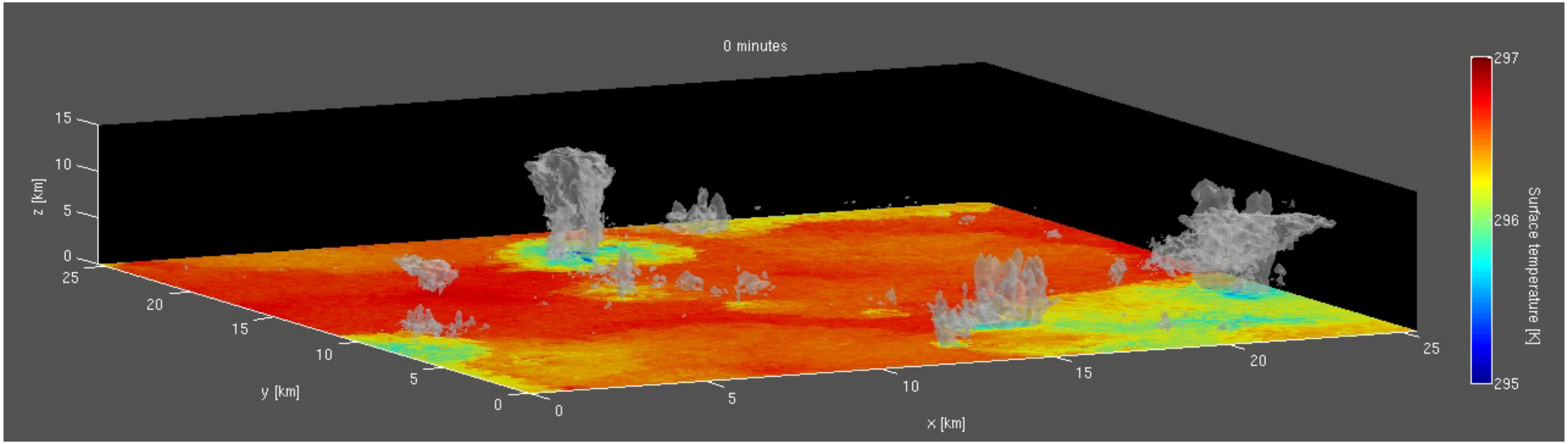
Radiative Convective Equilibrium

Clouds over near-surface temperature



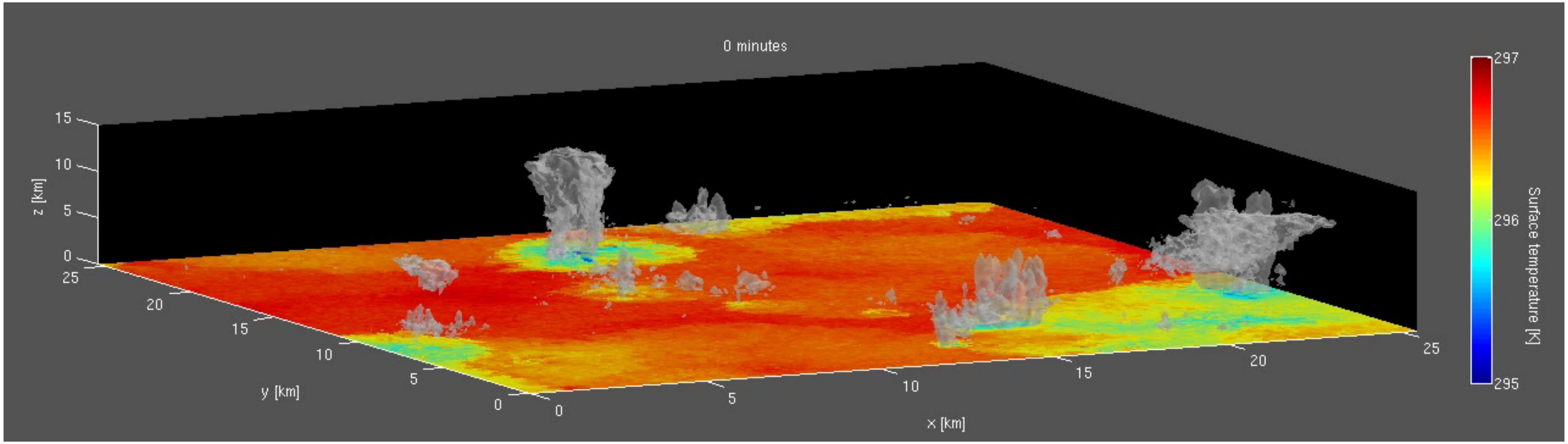
Radiative cooling in the interior of the atmosphere => destabilizes

Convective updrafts bring moist, high energy air from surface to interior of the atmosphere => stabilizes

Convective downdrafts bring cold&dry, low energy air from interior to surface => stabilizes

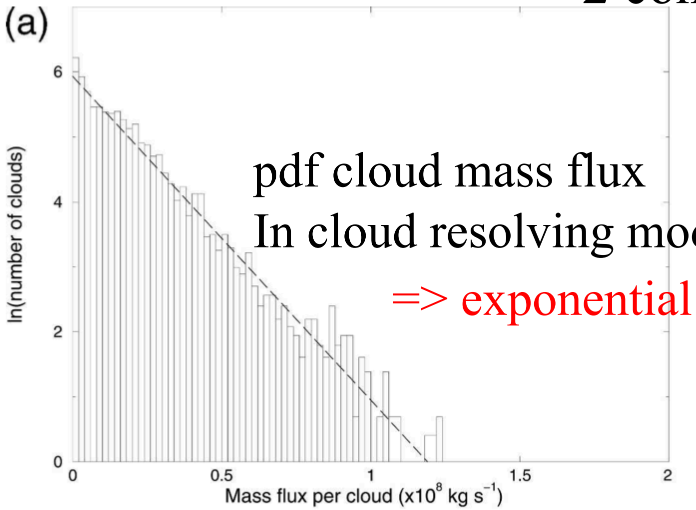
Radiative Convective Equilibrium

Clouds over near-surface temperature



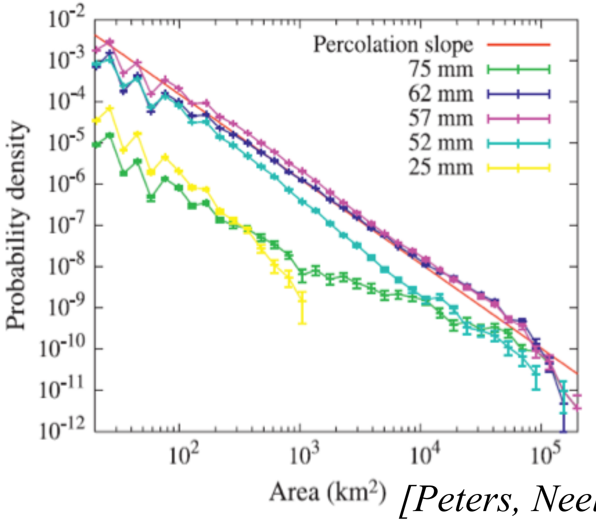
Our question: What is the spatial distribution of deep clouds?

2 contradictory results :



pdf cloud mass flux
In cloud resolving model
=> exponential

[Cohen and Craig, JAS 2006]



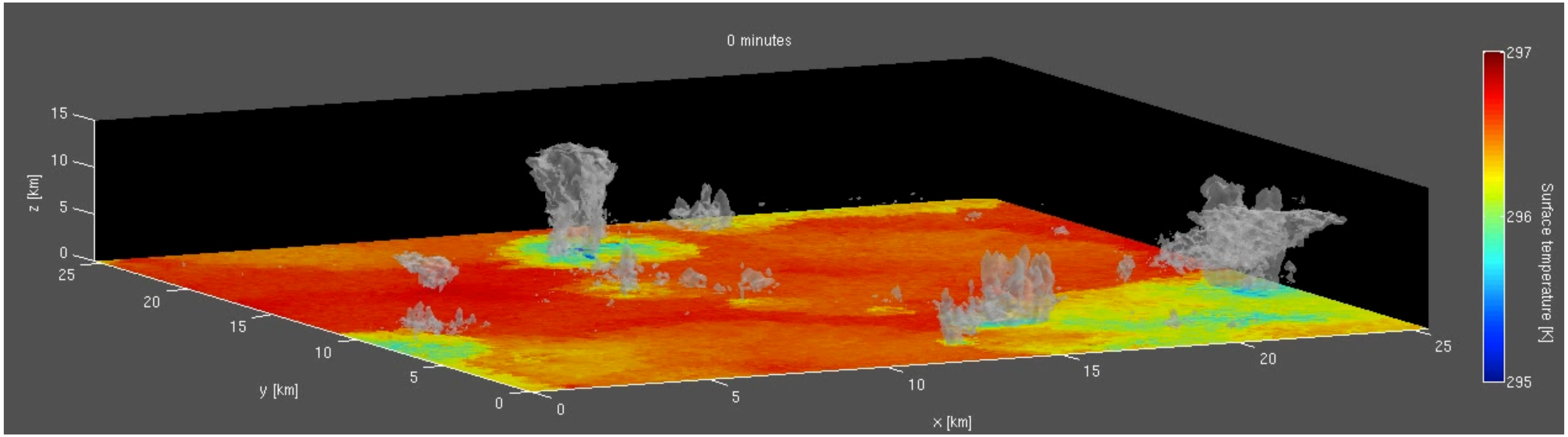
pdf cloud area in observations
=> power law

[Peters, Neelin and Nesbitt, JAS 2009]

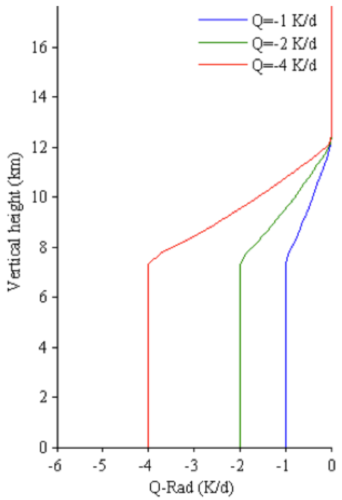
Cloud-resolving model SAM

- Anelastic momentum, continuity and scalar conservation equations
- Fixed SST, square doubly-periodic domain, no rotation *[Khairoutdinov & Randall, JAS 2003]*
- Run to statistical RCE (Radiative – Convective Equilibrium)

Clouds over near-surface temperature



Imposed radiative cooling rates

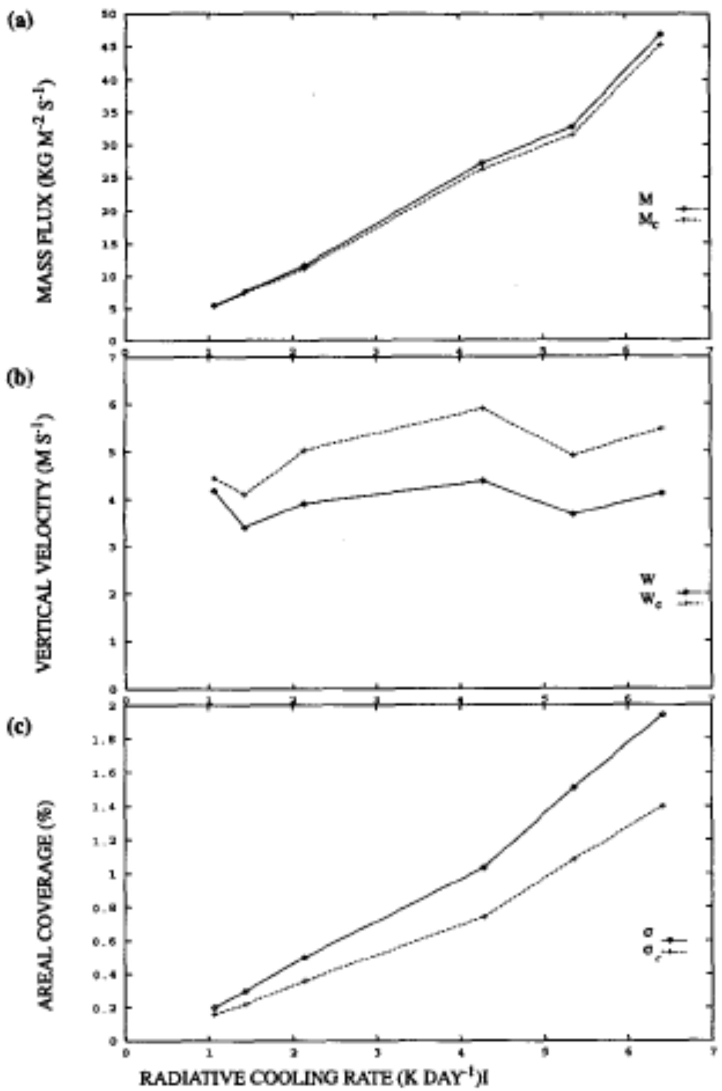


Definition of clouds $\begin{cases} q_{cld,2400m} > 5x10^{-3} \text{ g/kg} \\ w_{2400m} > 1 \text{ m/s} \end{cases}$ => Same results

[Cohen & Craig JAS 2006]

Radiative Convective Equilibrium

But pdf of cloud area/mass flux should be the same:



Mass flux ~ w_{cld} * A_{cld}

w_{cld}

A_{cld}

⇒ Increase in flux due to area increase

⇒ vertical velocities in updrafts ~ constant

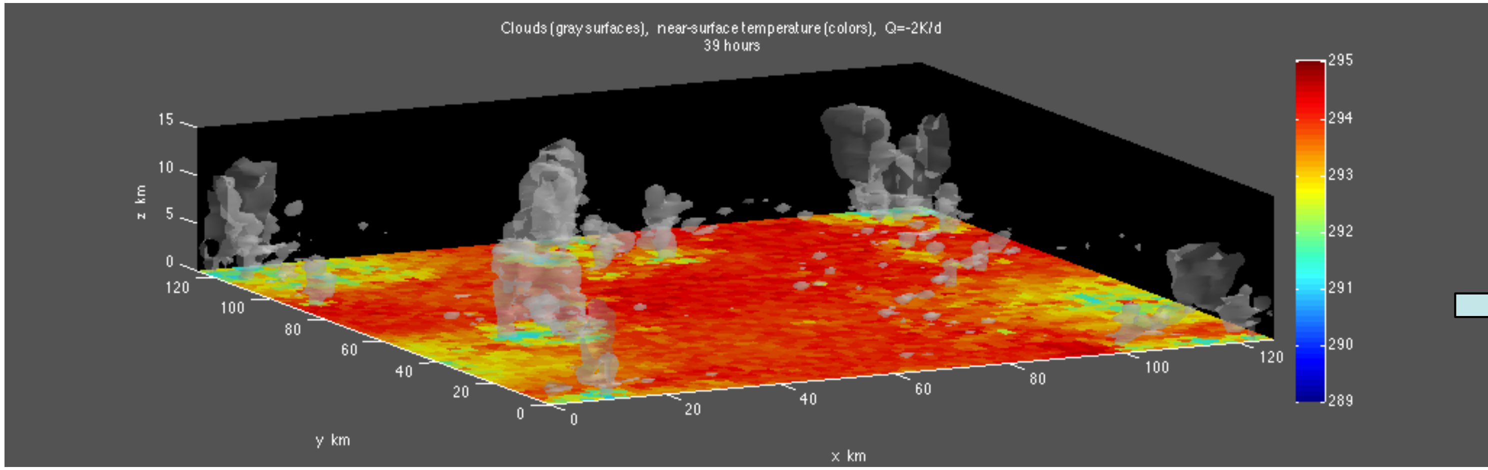
⇒ Despite added cooling, atmosphere stays close to moist adiabat, CAPE ~ constant

[Robe & Emanuel JAS 96, Kuang JAS 2010]

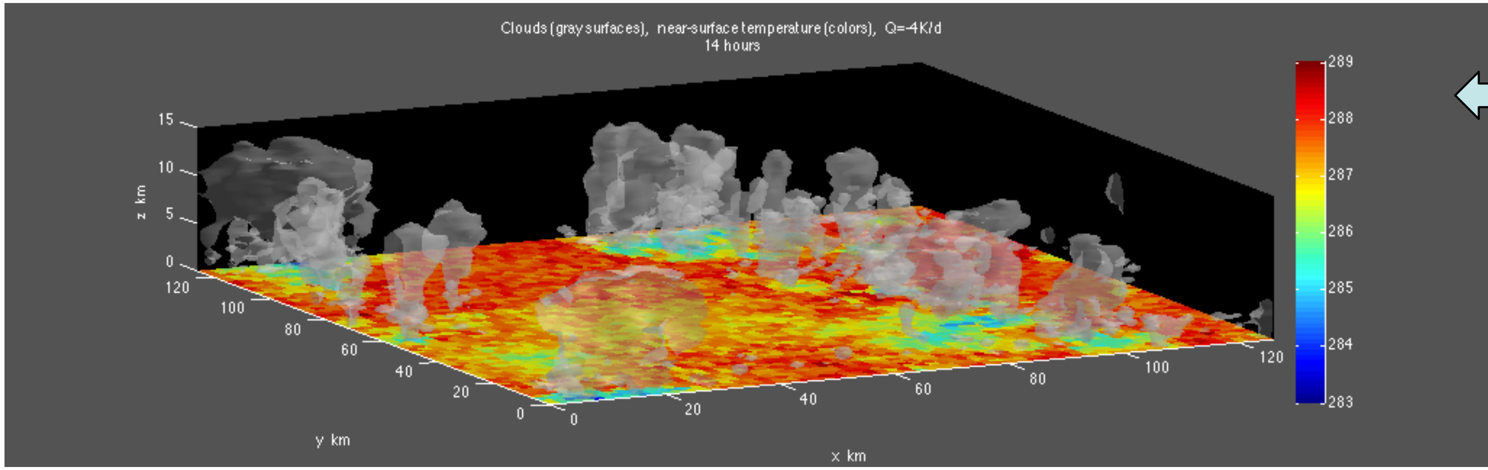
Radiative Convective Equilibrium

But pdf of cloud area/mass flux should be the same:

Q_{rad}



$2xQ_{rad}$



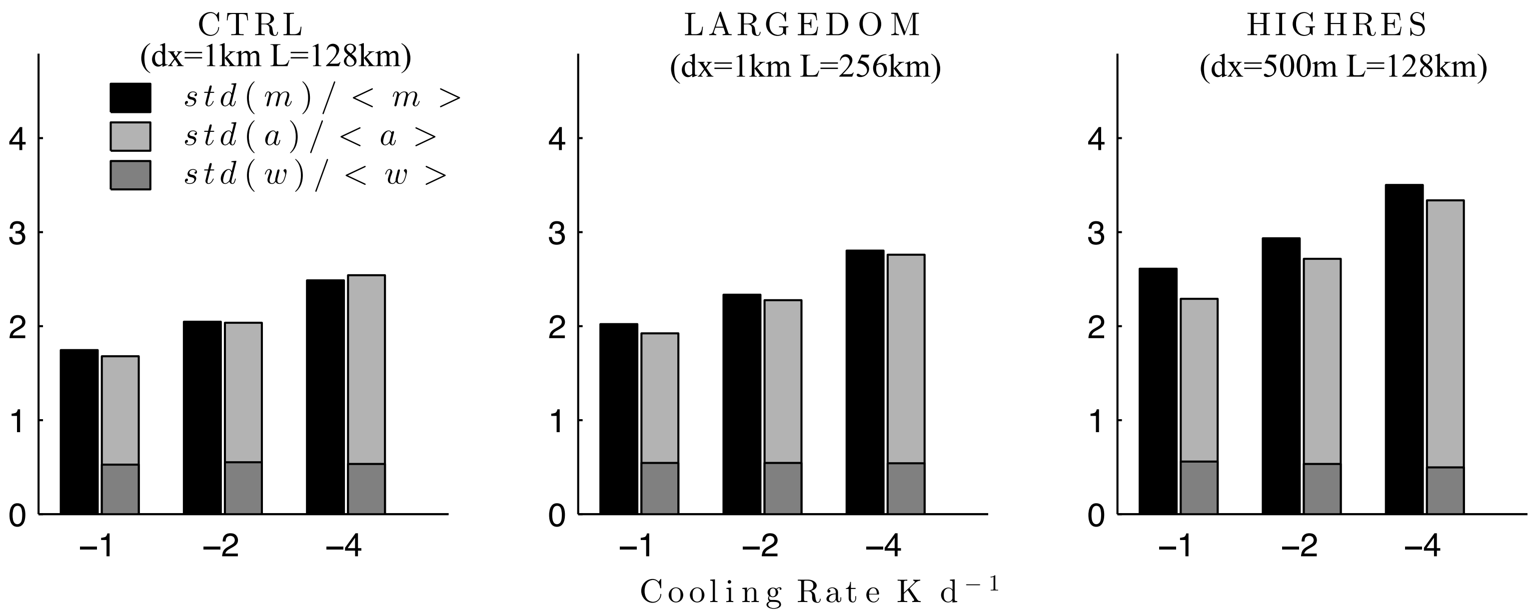
Increased cooling => increased cloud areal coverage

More cooling ⇔ more convective mass flux through increased convective area

Radiative Convective Equilibrium

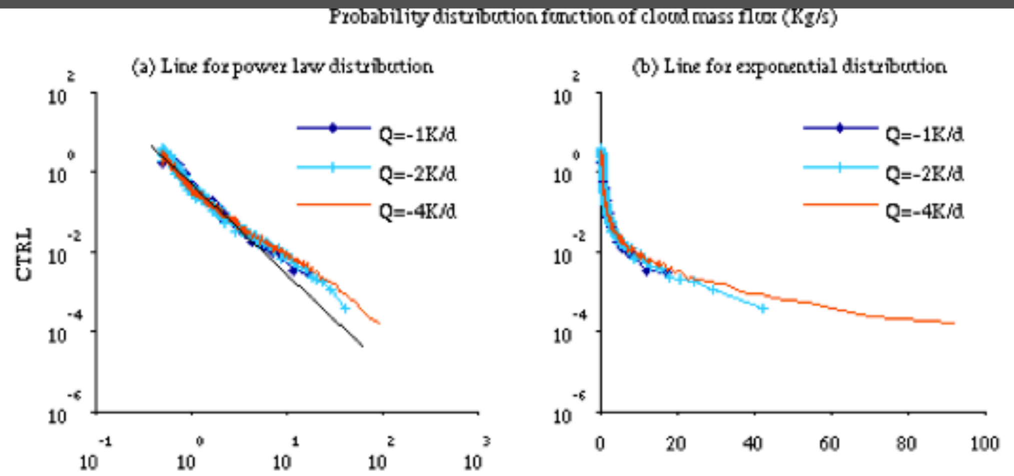
But pdf of cloud area/mass flux should be the same:

For each cloud i: $m_i = \rho\, a_i\, w_i$



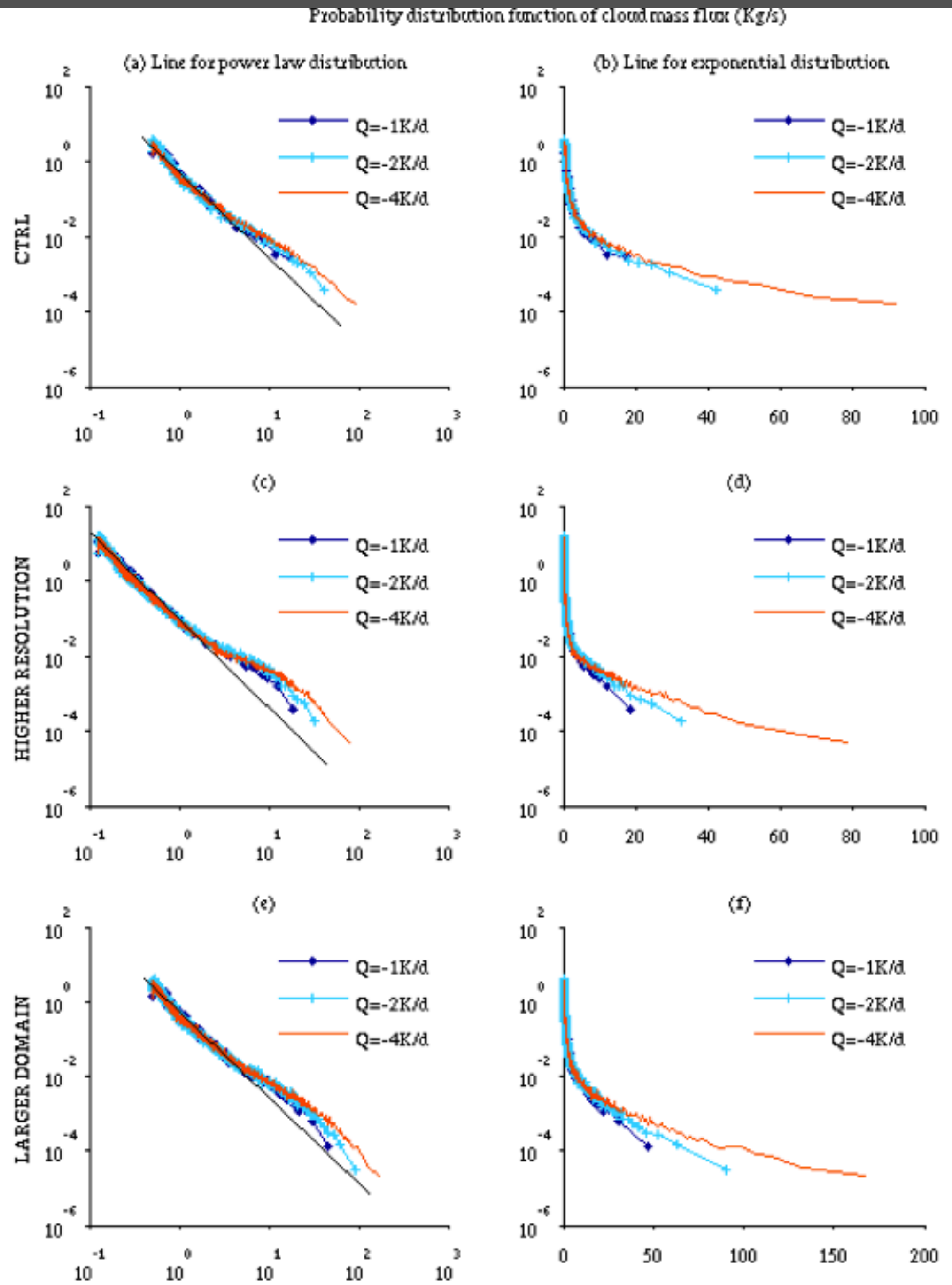
=> Variability of w << variability of either a or m

Radiative Convective Equilibrium



⇒ Power law
with exponential tail

Radiative Convective Equilibrium



⇒ Power law
with exponential tail

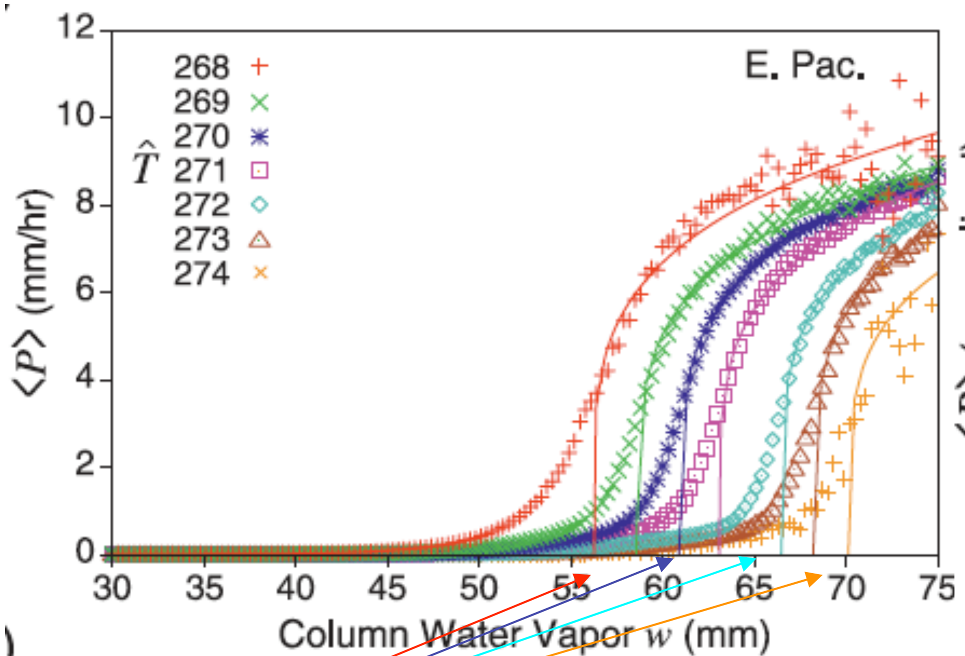
Why power law?...

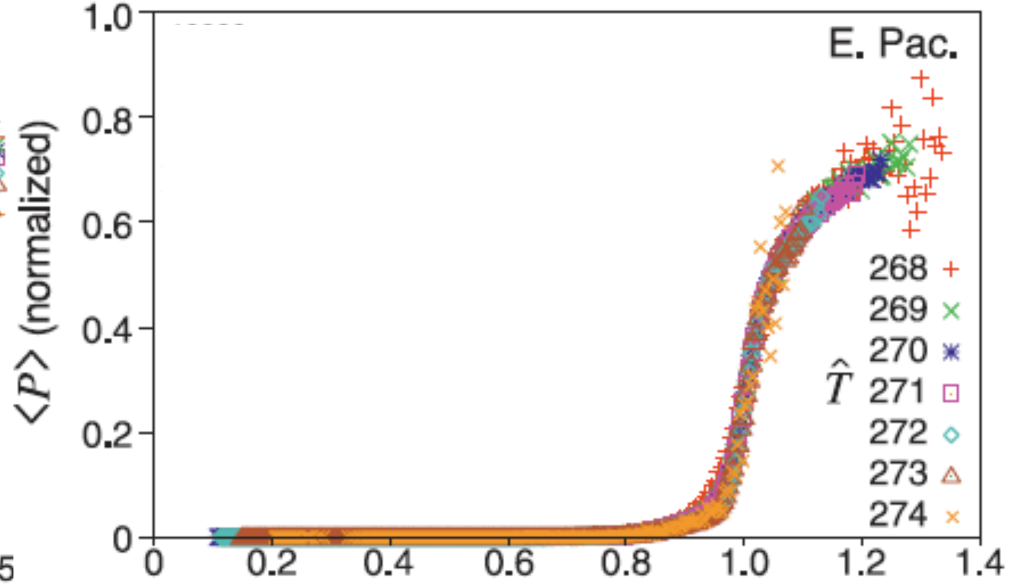
Radiative Convective Equilibrium

Deep convection = critical phenomenon ?

Universal moisture-precipitation relationship (depends on temperature)

TRMM instantaneous 0.25 x 0.25 degree data





w_c dependence on T does NOT match WV_{SAT}

Actually matches lower tropospheric $WV_{LT,SAT}$

[Peters & Neelin Nature Phys 2006
Neelin, Peters & Hales JAS 2009]

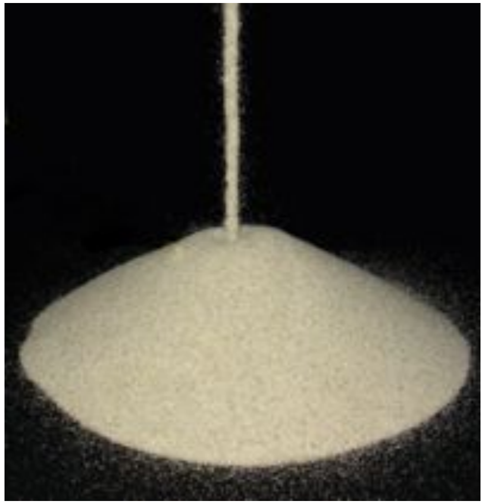
Theory:

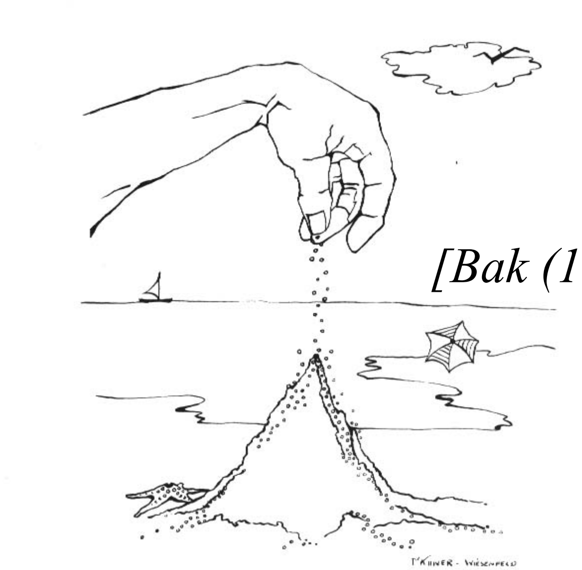
Convection is an instance of SOC (self-organized criticality)

Precipitation (order parameter) critical wrt water vapor (tuning parameter)

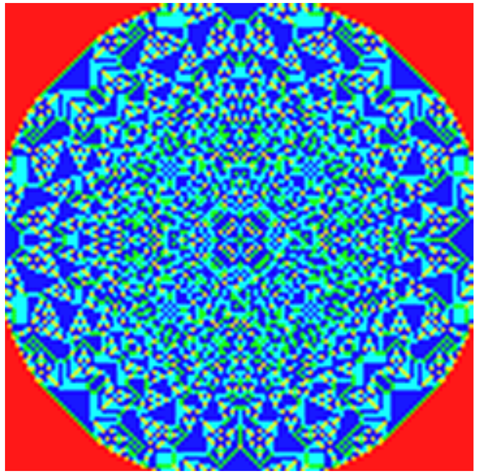
Radiative Convective Equilibrium

Self-Organized criticality





[Bak (1996)]



40000 grains dropped on center of 120x120 lattice, zc=4

Open boundaries + add sand

$\Rightarrow$ periodic avalanches occur, the size of which follow a power law

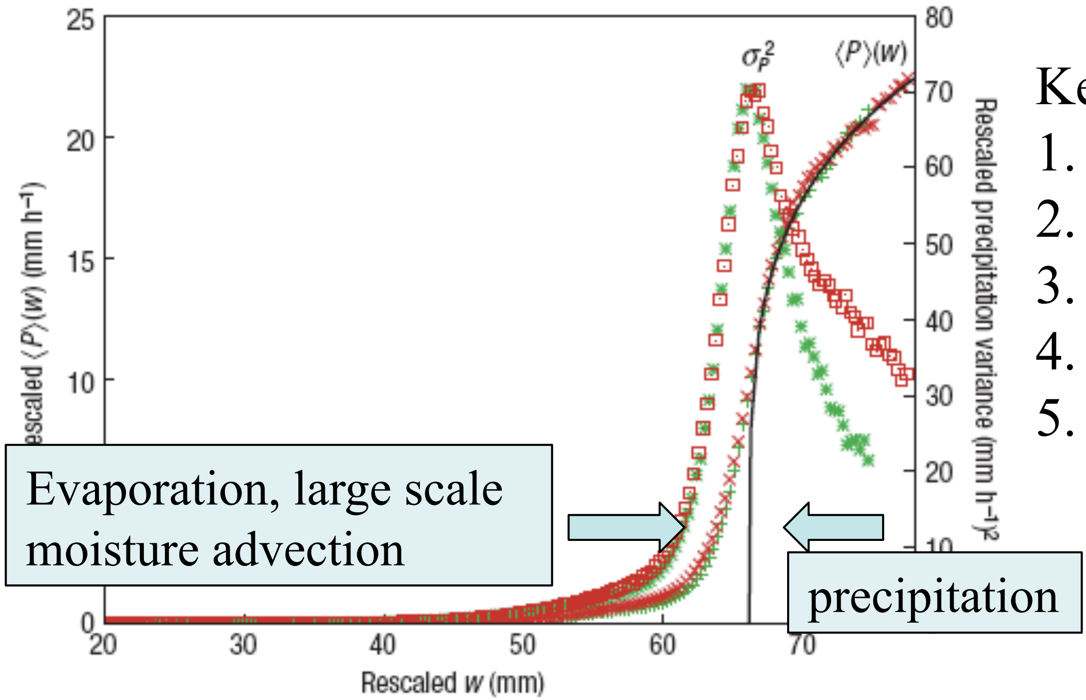
scale free, long-range correlation

$\Rightarrow$ attracted to its critical state: slope approaches the critical slope

NO tuning parameter (unlike eg temperature for phase transition)

=> criticality is “self-organized”

Radiative Convective Equilibrium



Key features supporting interpretation:
1. universal relationship
2. power-law fit
3. max variance near "critical point"
4. Scale free behavior (hard to test)
5. consistency w/QE postulate

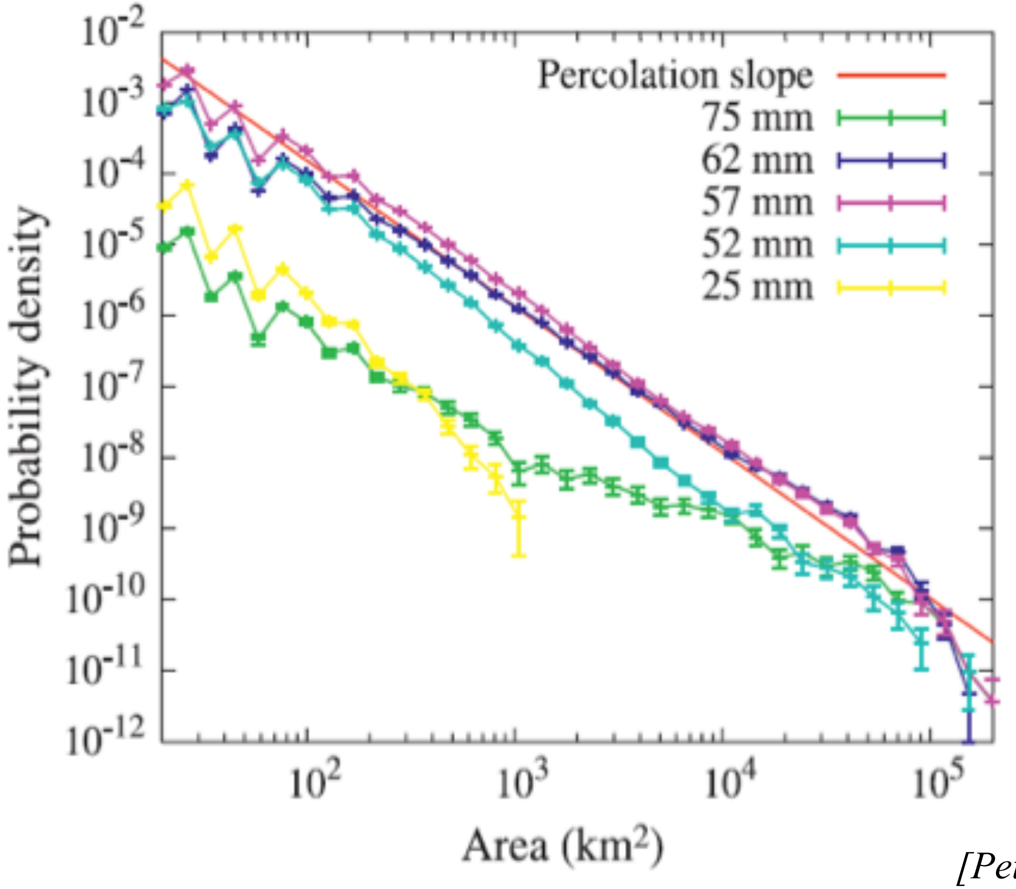
"…the attractive QE (quasi-equilibrium) state… is the critical point of a continuous phase transition and is thus an instance of SOC (self-organized criticality)"

[Peters and Neelin, Nature Phys. 06]

Radiative Convective Equilibrium

⇒ pdf of cluster size (clouds) follows a power law

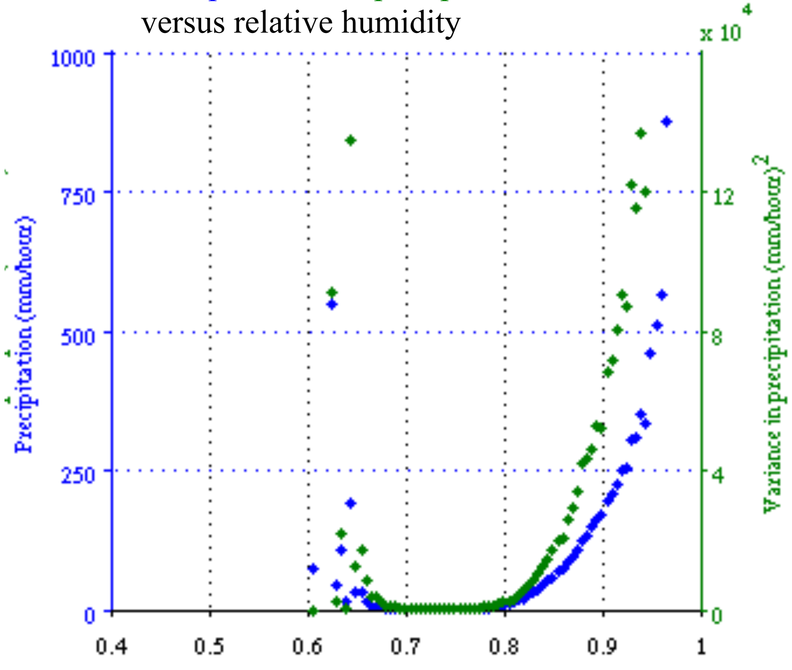
⇒ 2D percolation exponent = -187/91 ≈ - 2.05



[Peters, Neelin and Nesbitt, JAS 2009]

Radiative Convective Equilibrium

Precipitation and precipitation variance
versus relative humidity



relative humidity

⇒ pickup of precip, but no leveling off at highest humidities

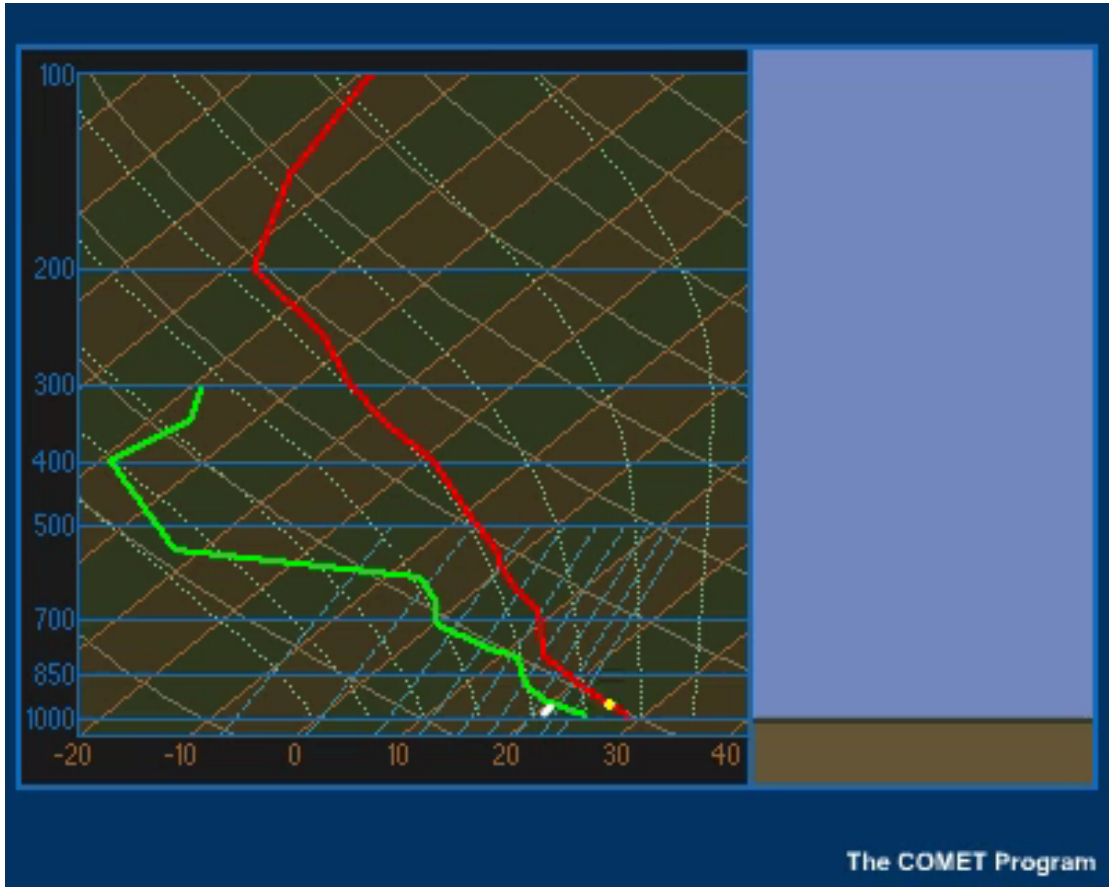
⇒ no max in variance

Radiative Convective Equilibrium

Moist convection

Parcel = yellow dot

EL equilibrium level



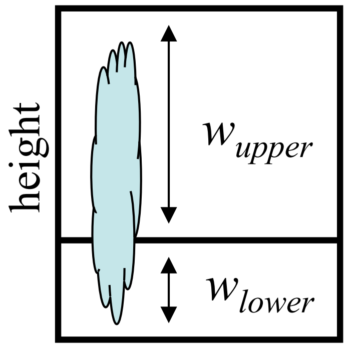
LFC level of free convection

CAPE: convective available potential energy

Instability dictates onset of convection
⇒ If critical, should be w.r.t. subcloud layer humidity
(dominates CAPE variance)

Radiative Convective Equilibrium

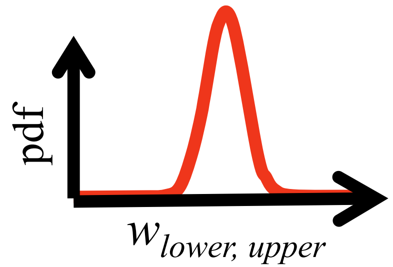
2 layer model

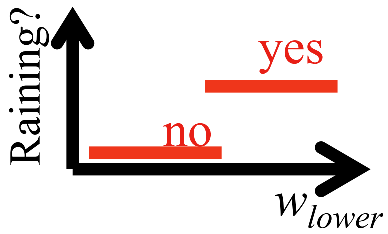


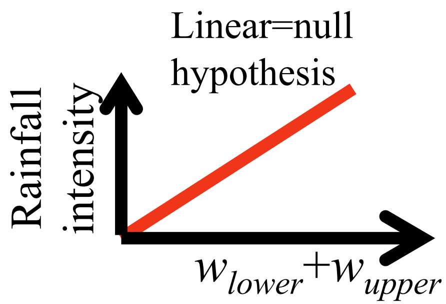
Free tropospheric water vapor

Subcloud layer water vapor

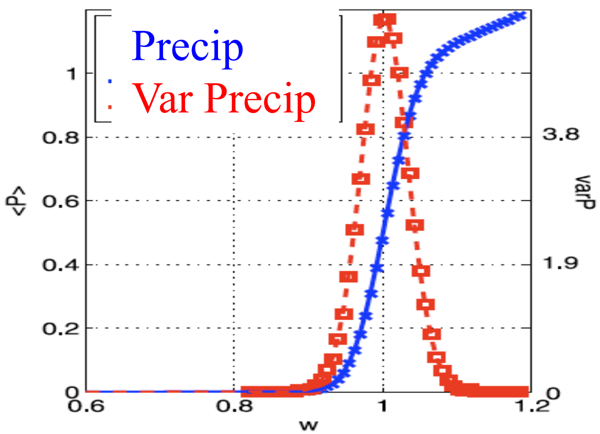
} independent random variables normally distributed

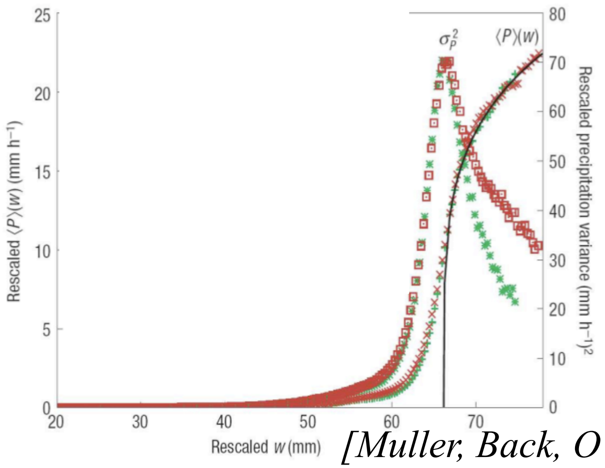






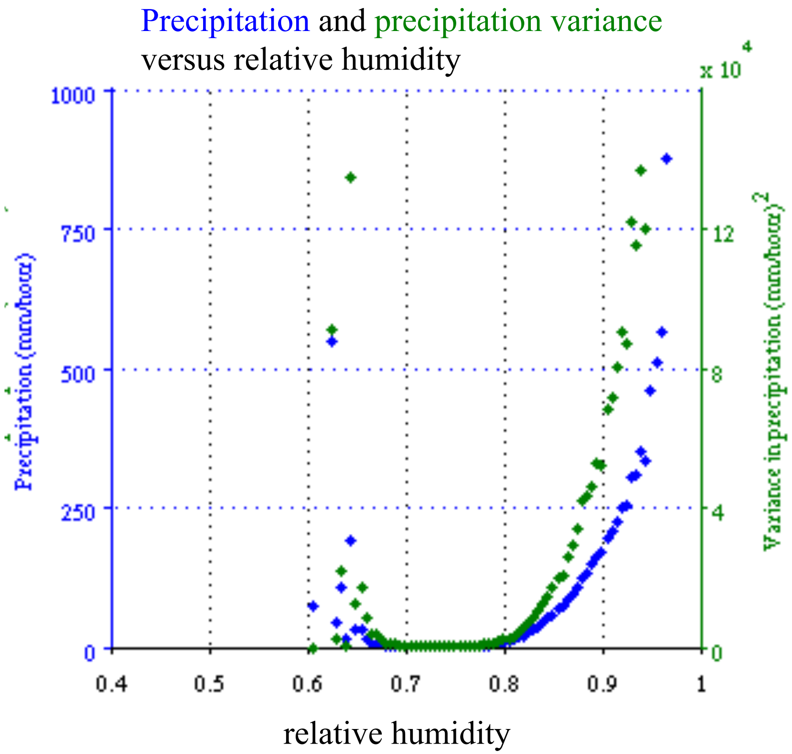
⇒

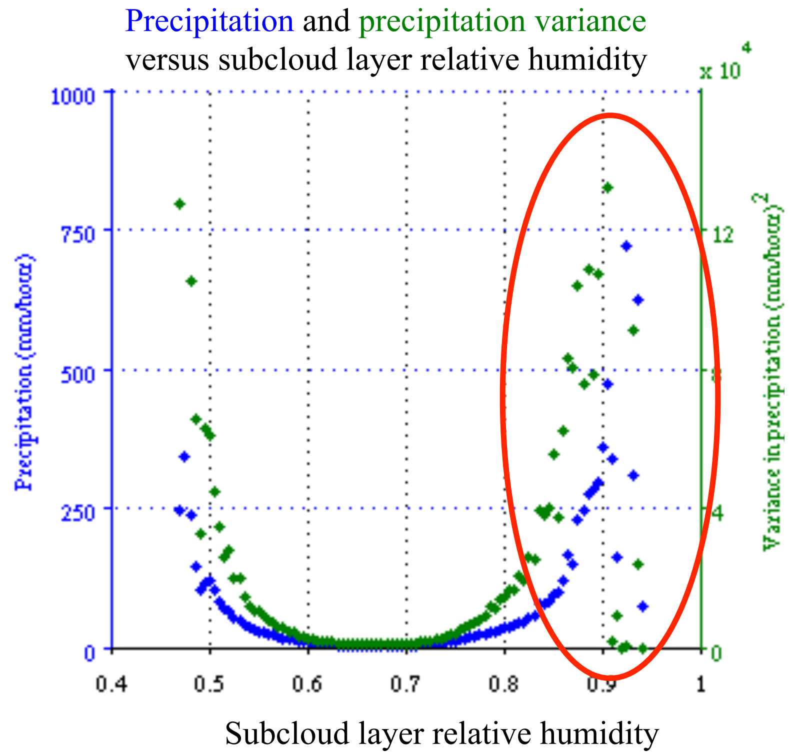




[Muller, Back, O'Gorman, Emanuel,GRL09]

Radiative Convective Equilibrium

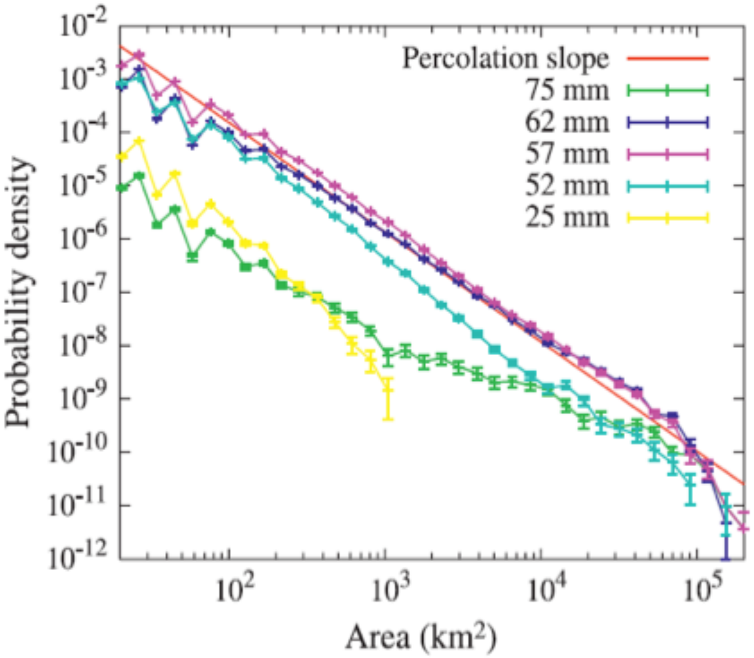




⇒ sharper pickup
⇒ increase in scatter above criticality, instead of the saturation of precipitation rates *[as in Posselt, Van den Heever, Stephens, Igel, J Clim 2012]*

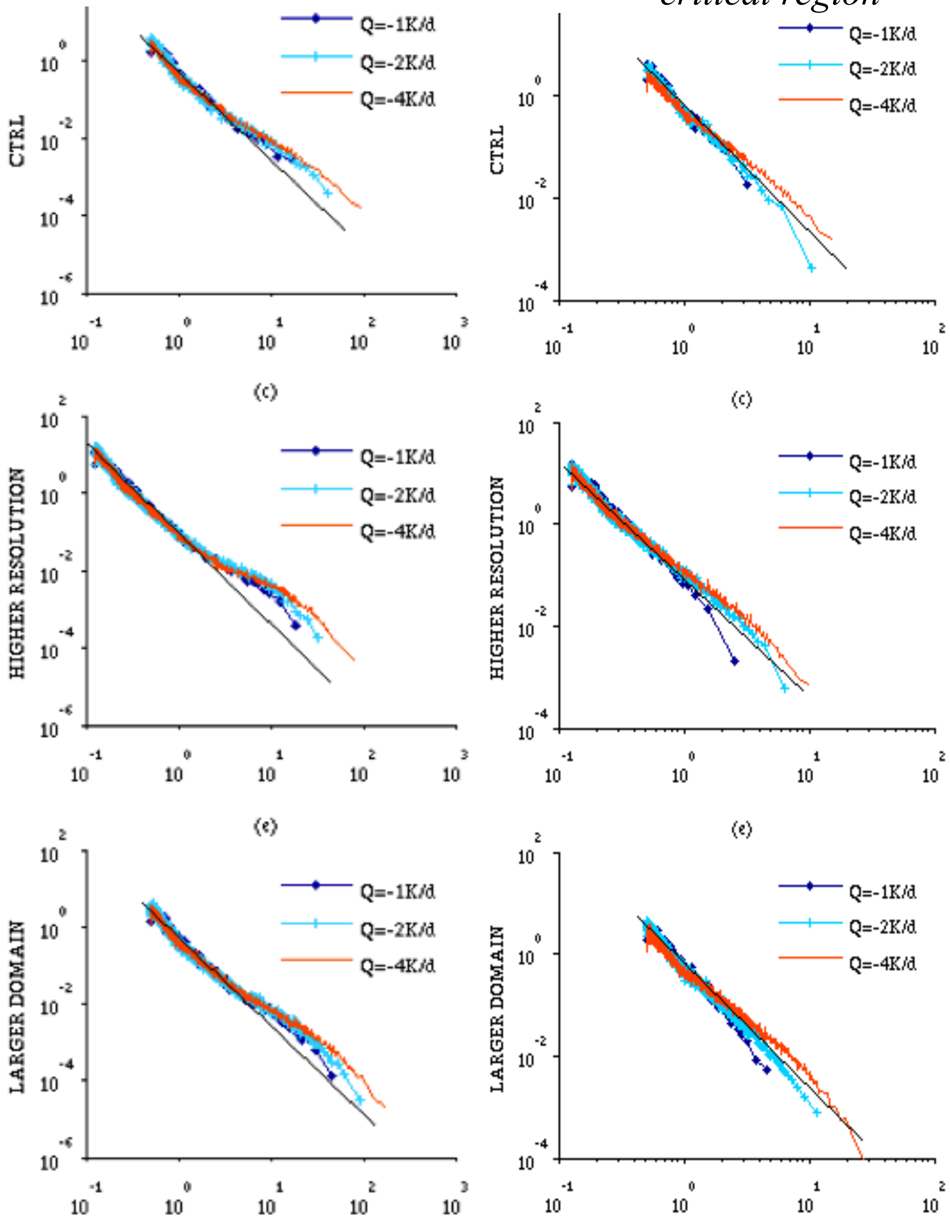
⇒ seems to be a peak in variance near criticality
⇒ However, noise and scatter above critical humidity => difficult to identify a unique variance maximum

Radiative Convective Equilibrium



[Peters, Neelin and Nesbitt, JAS 2009]

pdf mass flux | *pdf mass flux in the critical region*



⇒ pdf of cluster size follows a power law

⇒ 2D percolation exponent = -187/91 ≈ - 2.05

BUT slope ≈ -2.3

Radiative Convective Equilibrium

SUMMARY PART 2: RADIATIVE – CONVECTIVE EQUILIBRIUM

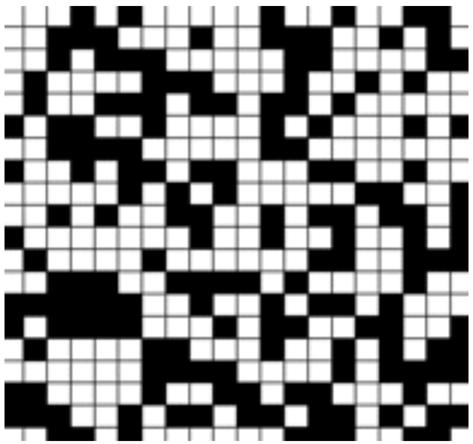
⇒ In « pop-corn » convection, the spatial distribution of deep clouds (pdf of cloud mass flux or cloud area) follows a power law

⇒ Broadly consistent with deep convection being critical phenomenon *[Neelin & Peters Nature Phys 06]*, albeit departures :

• if critical, should be wrt low-level humidity (measures instability)

[Muller, Back, O'Gorman, Emanuel,GRL 2009]

Physical picture :



At each site, probability to have a cloud $P_{cloud}=P\{w_{lower}>w_{lower,crit}\}$

• critical exponent (-2.3) close but consistently steeper than the 2D percolation exponent (-2.05) : largest clouds less likely than expected from theory. Possibly because:

- Neglected entrainment
- Neglected reevaporation of rain &downdrafts

=> Negative feedback on deep convective clouds

[Raja & Muller, QJRMS in prep 2015]

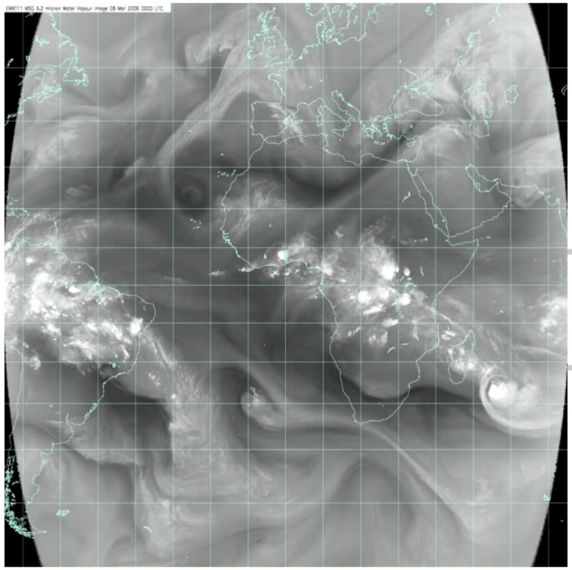
Outline

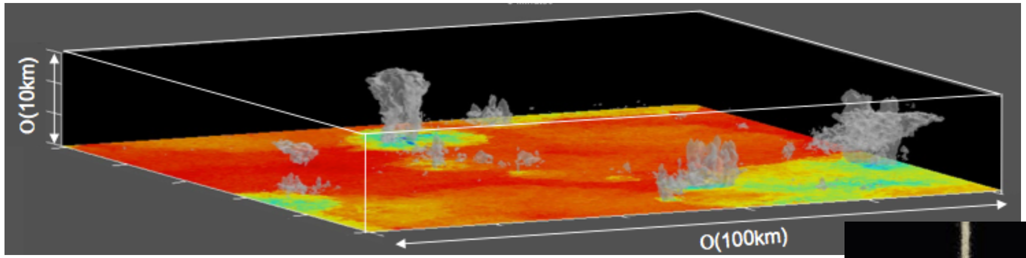
- Clouds in the climate system

- Spatial distribution of tropical deep convection

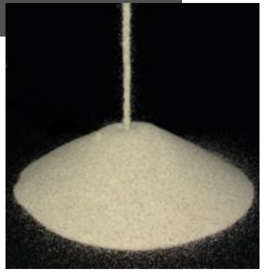
Radiative-convective equilibrium
Clouds over surface temperature

Water vapor from satellite

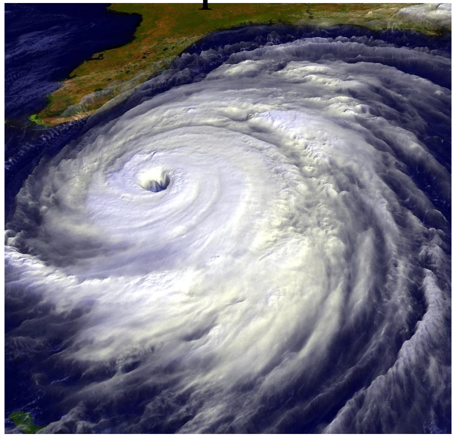




Tropical « pop corn » convection



- Spontaneous organization of deep convection

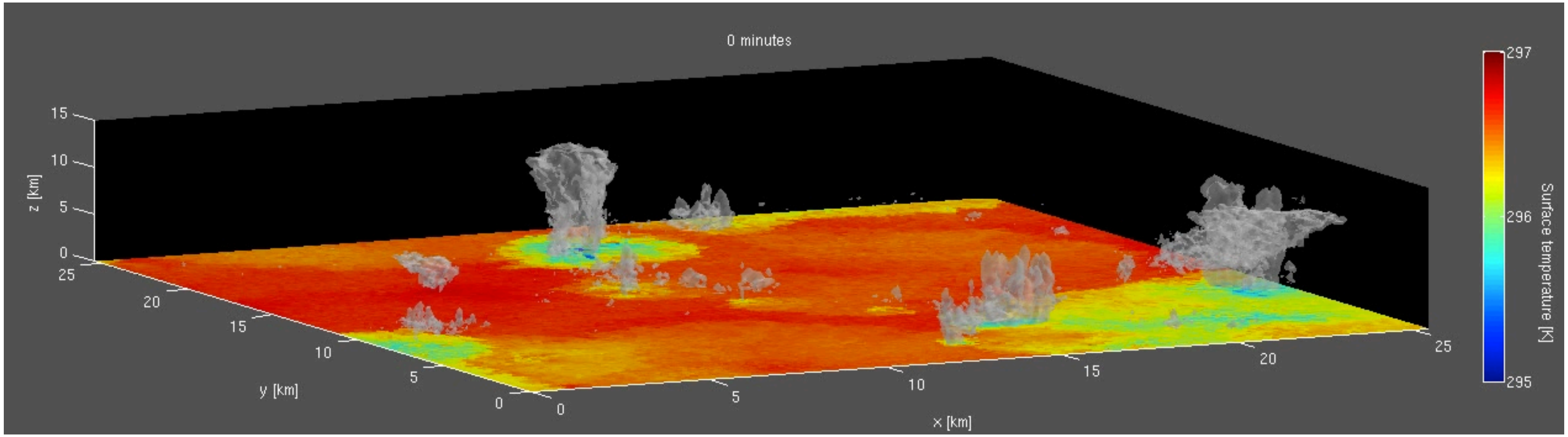


[Raymond, Zeng QJRMS 2000;
Bretherton, Blossey, Khairoutdinov, JAS 2005;
Sobel, Bellon, Bacmeister GRL 2007;
Muller, Held, JAS 2012;
Tobin, Bony, Roca, J Clim 2012;
Emanuel, Wing, Vincent JAMES 2013;
Craig and Mack, JGR, 2013;
Jeevanjee, Romps, GRL 2013;
Khairoutdinov, Emanuel, JAMES 2013;
Shi, Bretherton JAMES 2014;
Bony et al, Nature Geoscience 2015]

Self-Aggregation

Radiative Convective Equilibrium (RCE)

Clouds over near-surface temperature

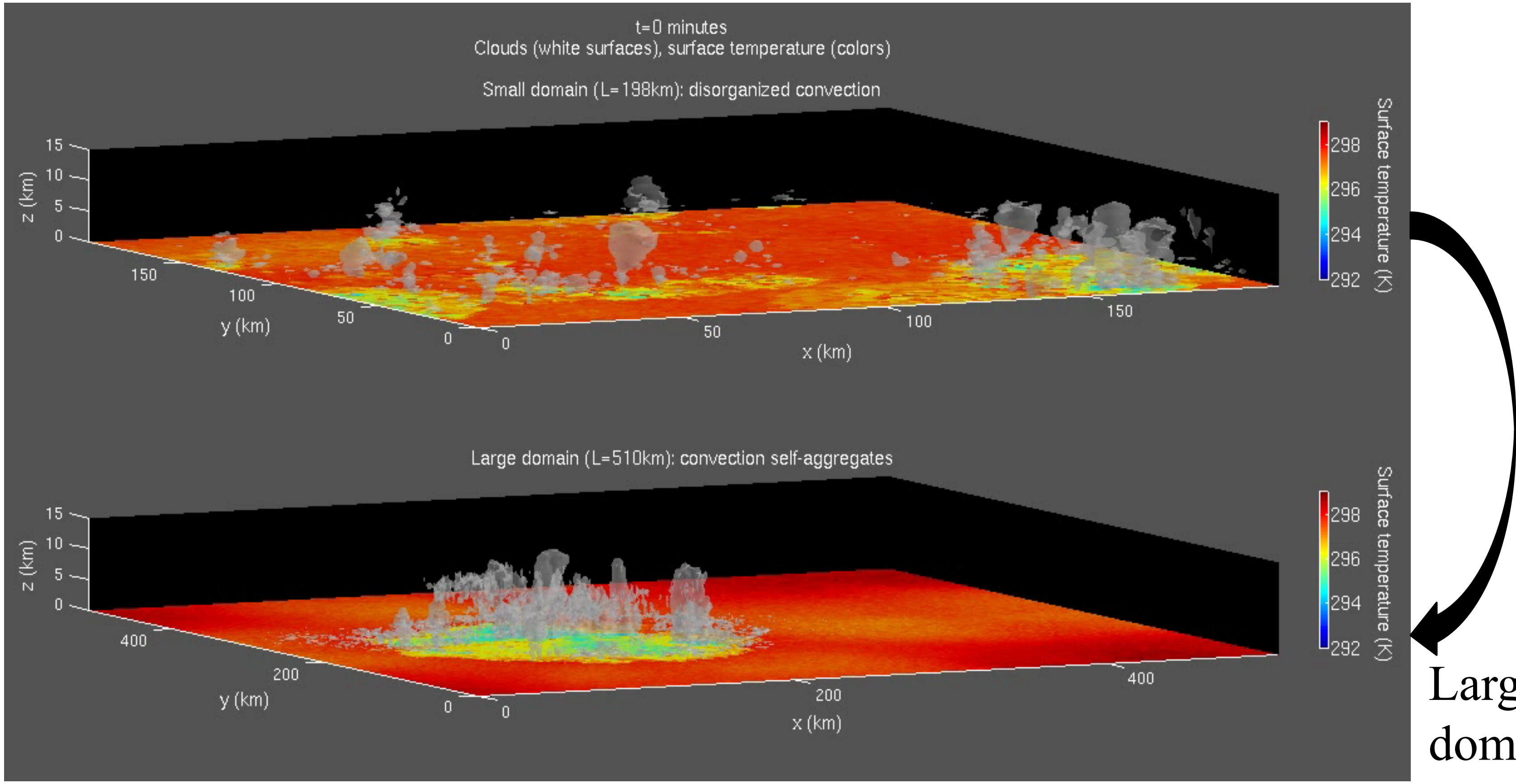


Self-aggregation = instability of disorganized RCE "pop corn" state

[Raymond, Zeng QJRMS 2000; Bretherton, Blossey, Khairoutdinov, JAS 2005; Sobel, Bellon, Bacmeister GRL 2007; Muller, Held, JAS 2012; Tobin, Bony, Roca, J Clim 2012; Emanuel, Wing, Vincent JAMES 2013; Craig and Mack, JGR, 2013; Jeevanjee, Romps, GRL 2013; Khairoutdinov, Emanuel, JAMES 2013; Shi, Bretherton JAMES 2014; Bony et al, Nature Geoscience 2015]

Self-Aggregation

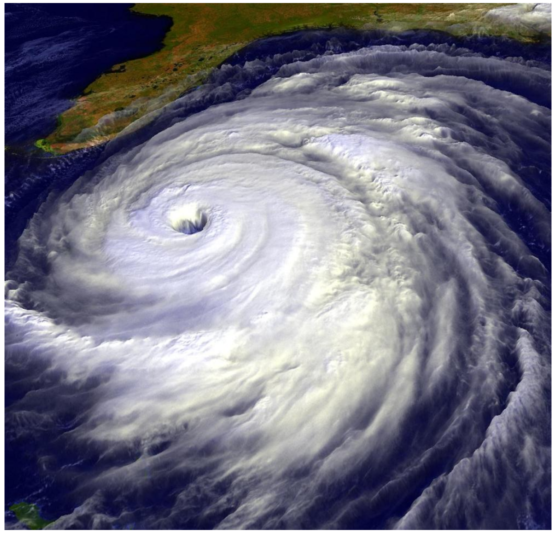
Clouds over near-surface temperature



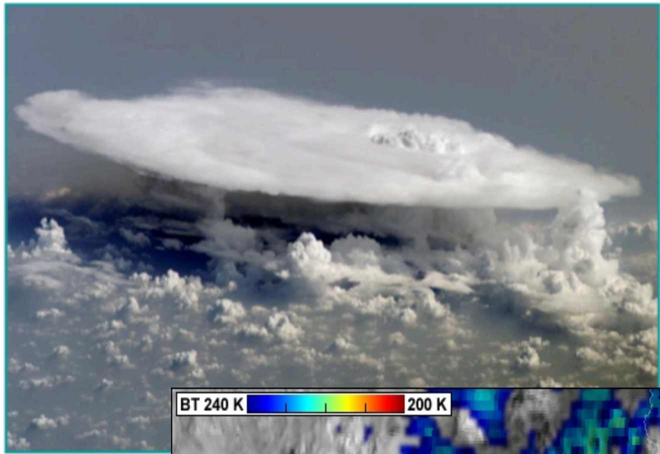
Larger domain => convection aggregates

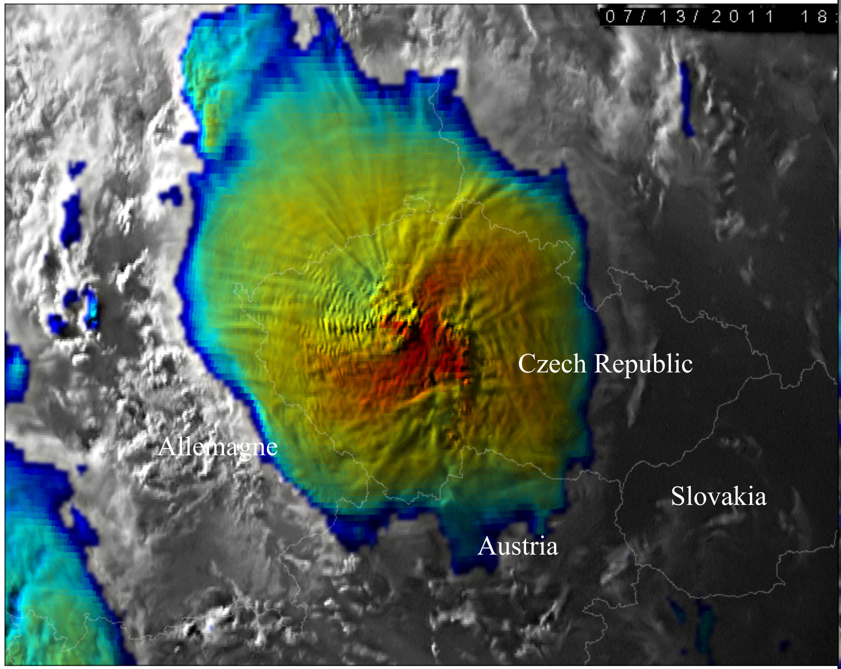
Self Aggregation: why do we care?

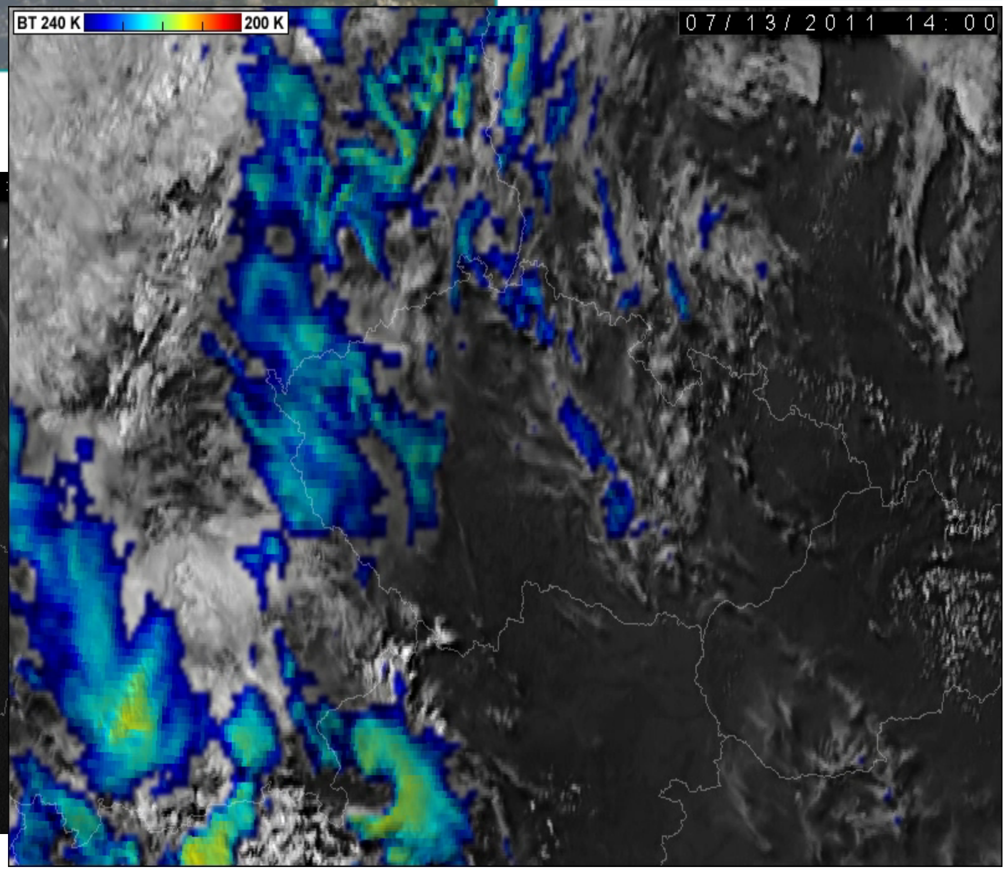
Hurricane Floyd



Mesoscale convective systems





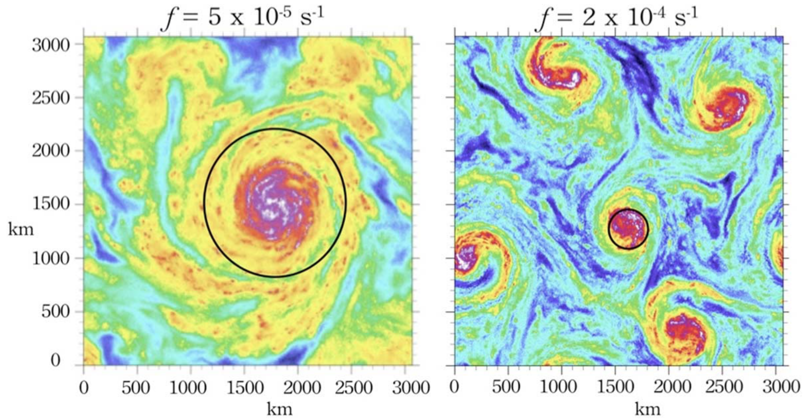


Self Aggregation: why do we care?

Feedback responsible for self-aggregation - Role in cyclogenesis ?

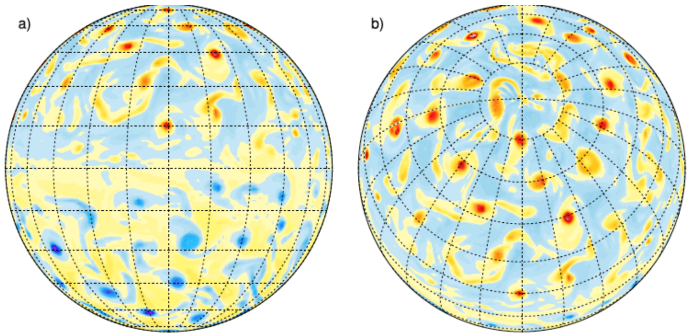
Add rotation => tropical cyclones « TC World »

Precipitable water PW (= vertically integrated water vapor)

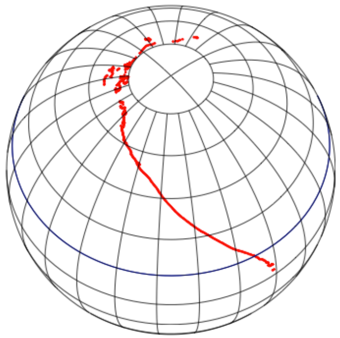


[Bretherton, Blossey, Khairoutdinov, JAS 2005; Khairoutdinov and Emanuel, JAMES 2013]

Relative vorticity at 850 hPa



trajectory of vortices



[Shi and Bretherton, JAMES 2014]

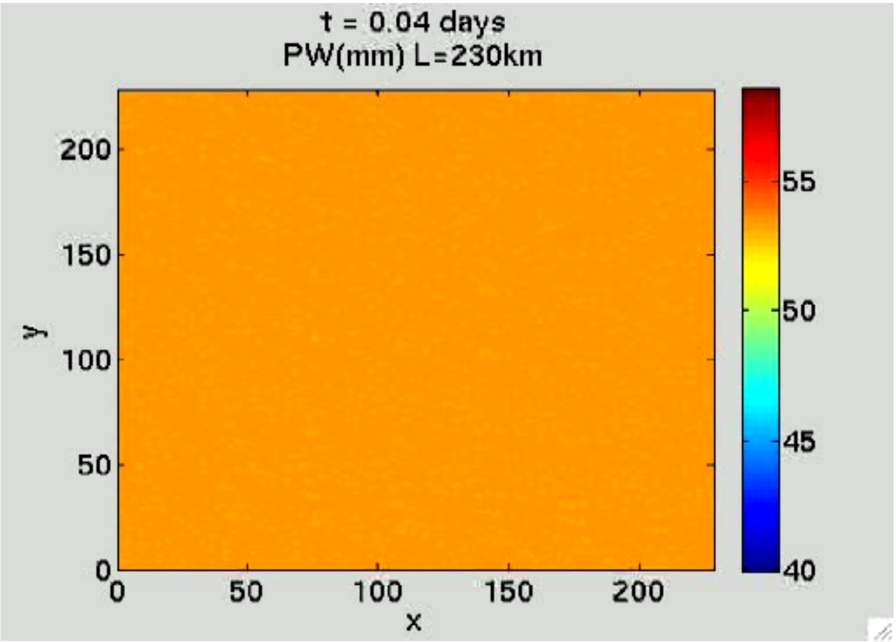
Self-aggregation of convection - Role in MJO ?

[Tobin et al, JAMES 2013
Yang and Ingersoll, JAS 2013]

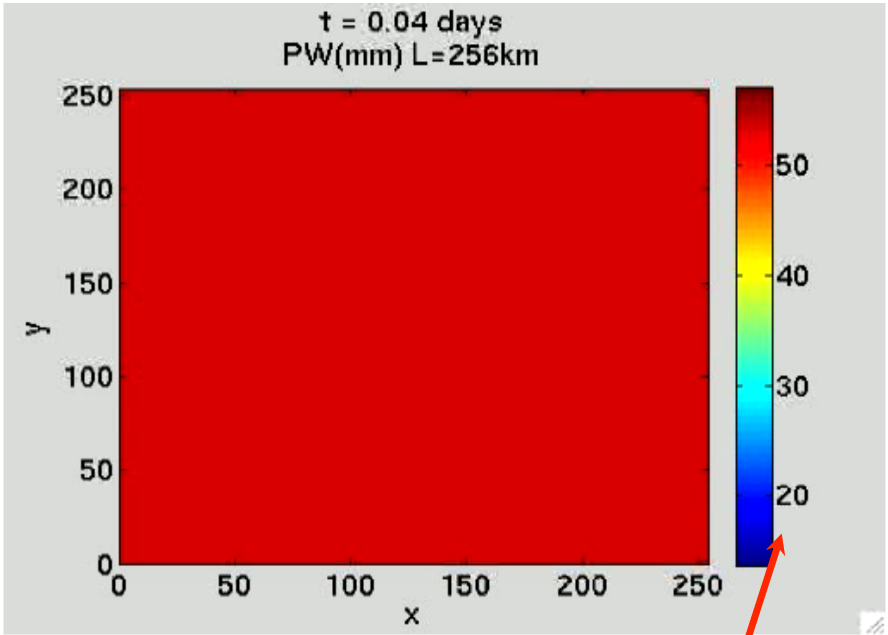
Self Aggregation: why do we care?

Top view of precipitable water PW (= vertically integrated water vapor)

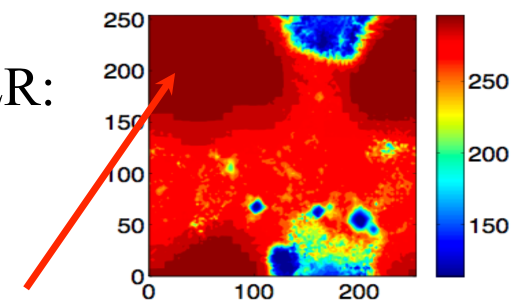
230km



256km



OLR:



⇒ Thermodynamic and radiative properties dramatically affected

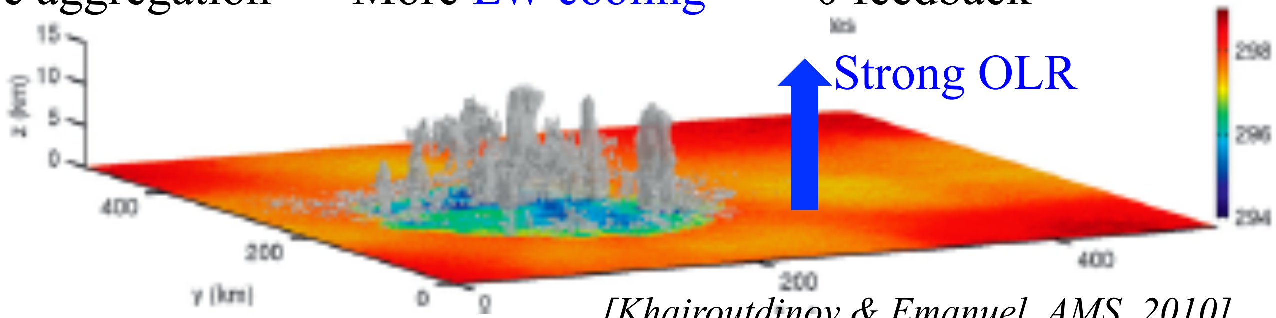
Self Aggregation: why do we care?

Sensitive to temperature : favored at warm and cold T.

[Emanuel, Wing, Vincent, JAMES 2013 Abbot J. Clim. 2014]

Self-aggregation regulates tropical climate?

Warmer temperatures => More aggregation => More LW cooling => <0 feedback

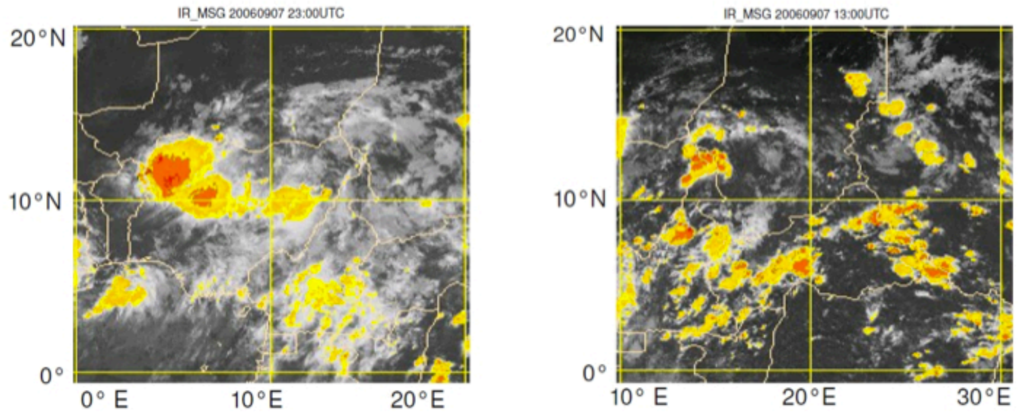


[Khairoutdinov & Emanuel, AMS, 2010]

Radiative impact poorly understood.

Observations suggest that SW warming may partly compensate LW cooling

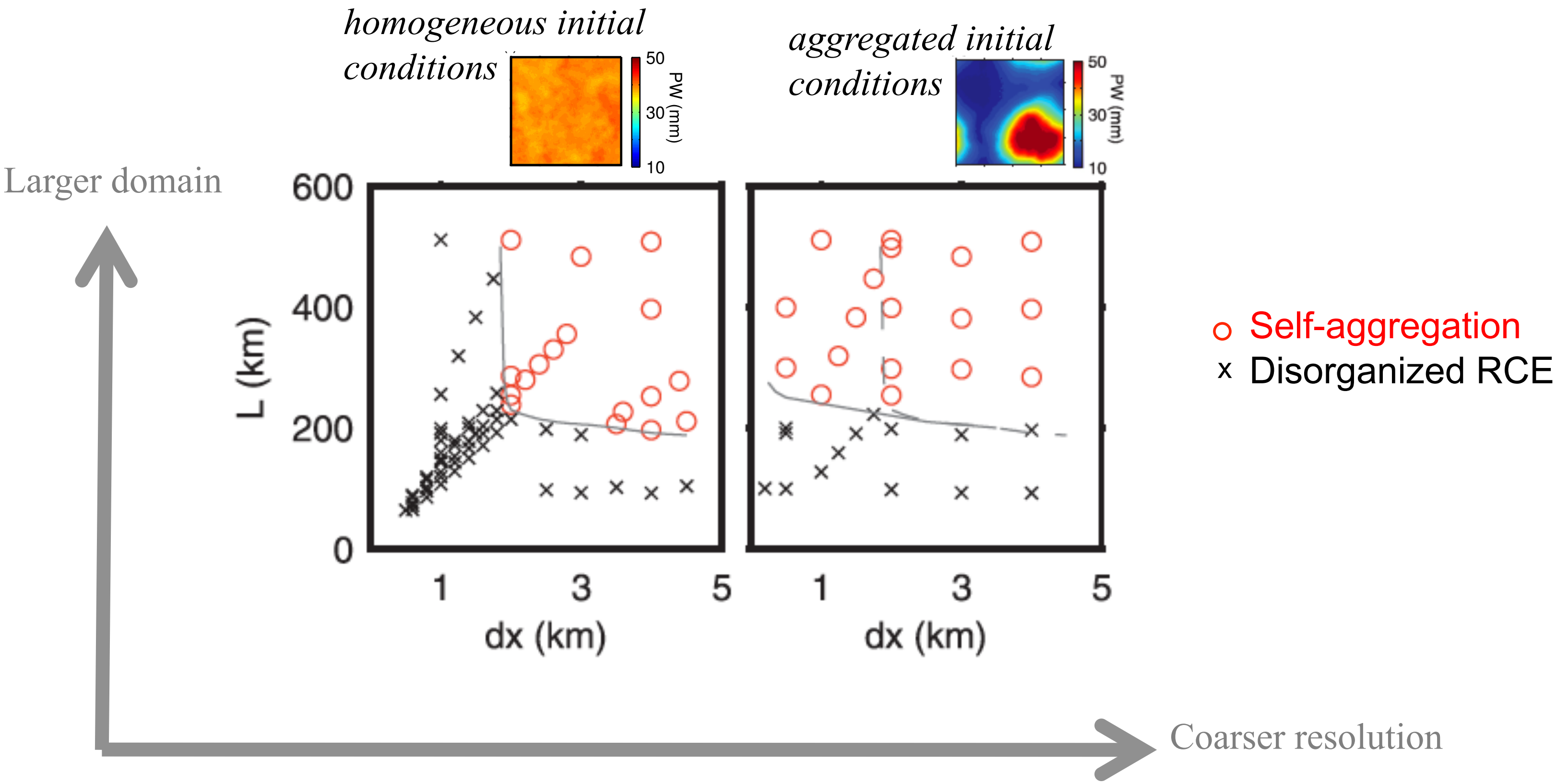
Still true at warmer T?



[Tobin, Bony, Roca, J.Clim 2012 Tobin et al, JAMES 2013]

Self-Aggregation: what we know

Hysteresis *[Khairoutdinov & Emanuel, AMS, 2010]*



Favored by
- large domains
- coarse resolution for onset

Self-Aggregation: what we know

Literature confusing…

- Cloud radiative processes, in particular in the longwave, have been shown to play a crucial role in the self-aggregation of convection. *[Muller, Held, JAS 2012]*

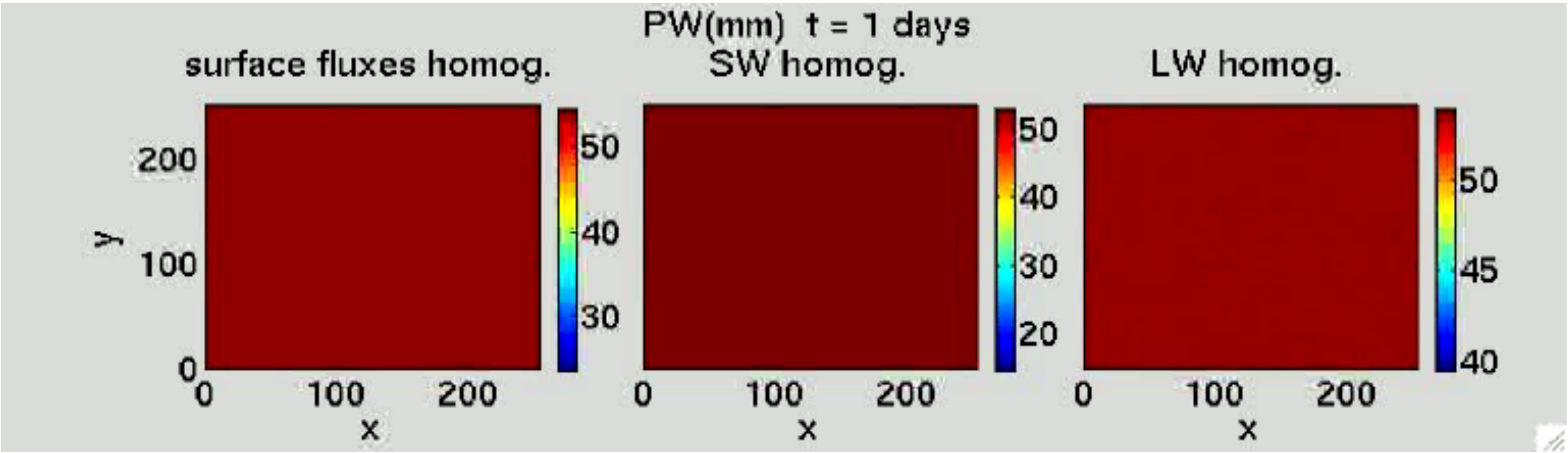
- Clear sky radiation has also been identified as a key ingredient in theoretical models of self-aggregation. *[Emanuel, Wing, Vincent JAMES 2013]*

- Cold pools have been shown to impact the aggregation as well. *[Jeevanjee, Romps, GRL 2013]*

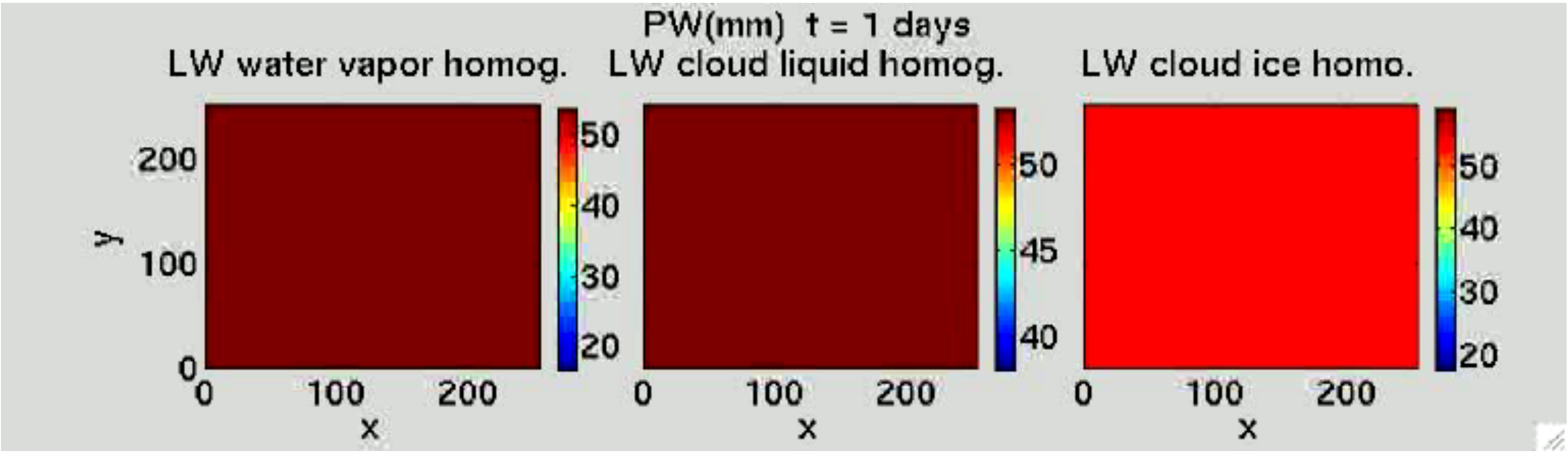
Our question: What aspect of each physical process matters for aggregation?

We address this question with idealized experiments

Self-Aggregation: low cloud LW



⇒ LW interactive radiation crucial



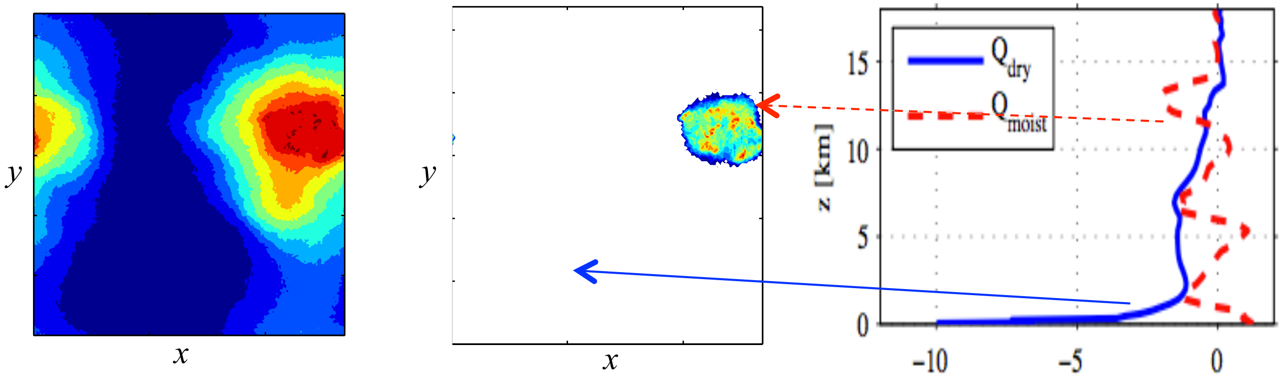
⇒ low cloud LW radiation crucial

What features of the interactive radiation are crucial?

Self-Aggregation: low cloud LW

PW(x,y) | moist region | Radiative cooling profiles (K/day) in and out moist region

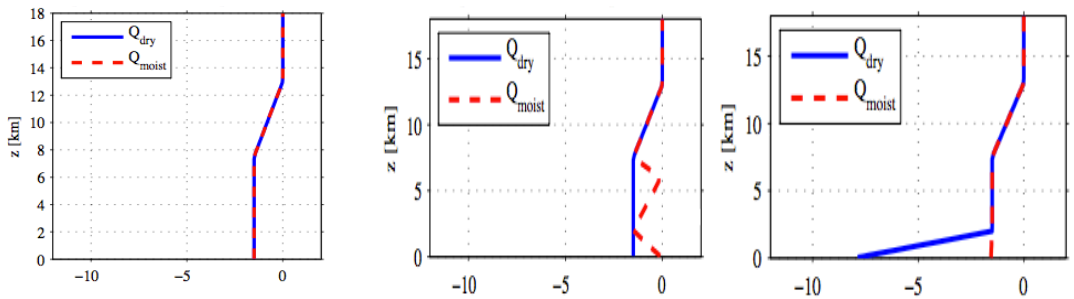
Interactive radiation



$$\frac{\partial T}{\partial t} = Q(T, qv, \cancel{qcloud}...) + ...$$

- $Q_{dry}(z)$ in dry region
- $Q_{moist}(z)$ in moist region

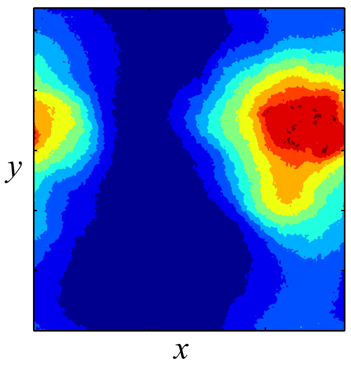
Imposed radiation



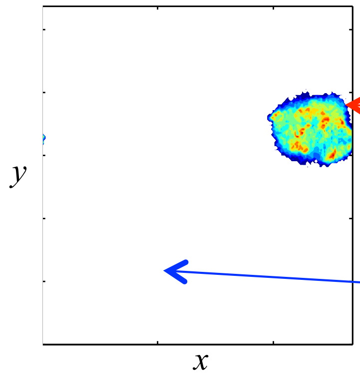
Self-Aggregation: low cloud LW

Interactive radiation

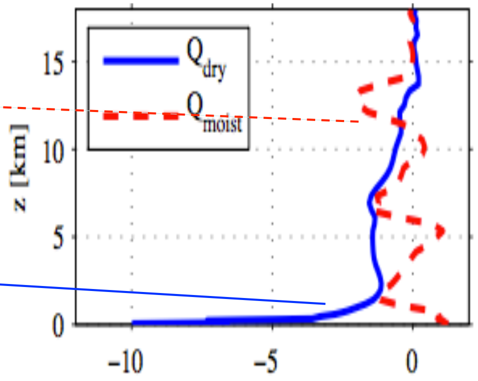
PW(x,y)



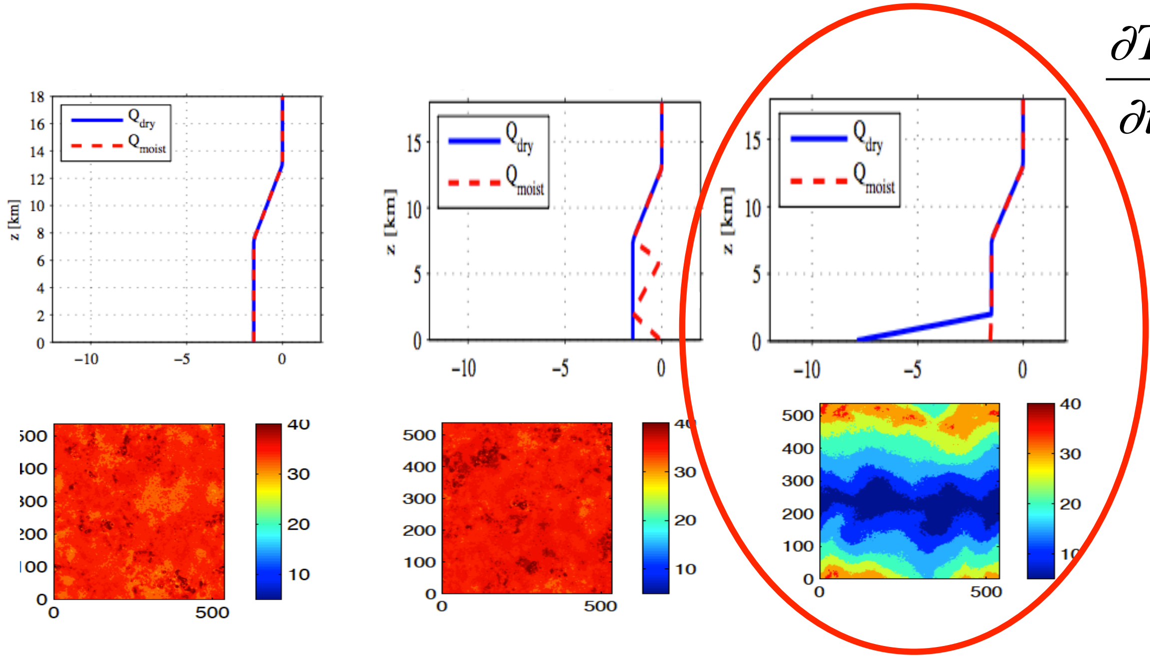
moist region



Radiative cooling profiles (K/day)
in and out moist region



Imposed radiation



$$\frac{\partial T}{\partial t} = Q(T, qv, \text{~~qcloud~~} \ldots) + \ldots$$

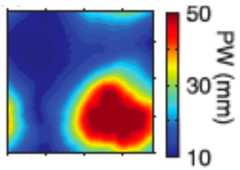
- $Q_{dry}(z)$ in dry region
- $Q_{moist}(z)$ in moist region

⇒ Variability in low level cooling causes spontaneous aggregation of convection

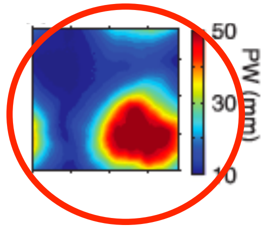
Self-Aggregation: high cloud LW

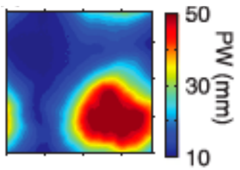
beginning of simulation

end of simulation

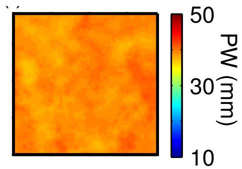


no low cloud radiation





no low cloud
no high cloud
radiation



⇒ high cloud + clear sky radiation can also maintain aggregation

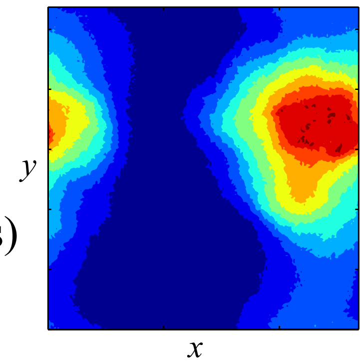
What features of the interactive radiation are crucial?

Self-Aggregation: high cloud LW

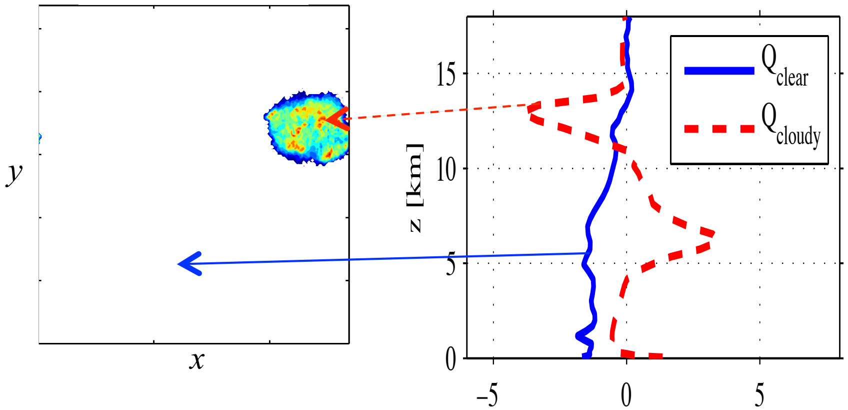
Radiative cooling profiles (K/day)
in and out high clouds

Interactive radiation (not low clouds)

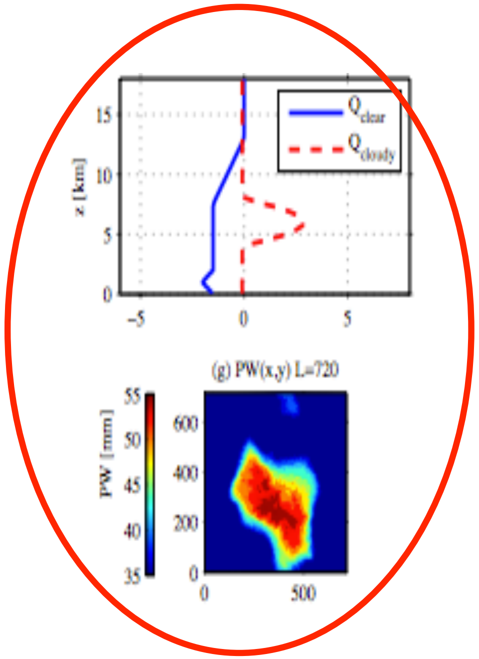
PW(x,y)



High clouds

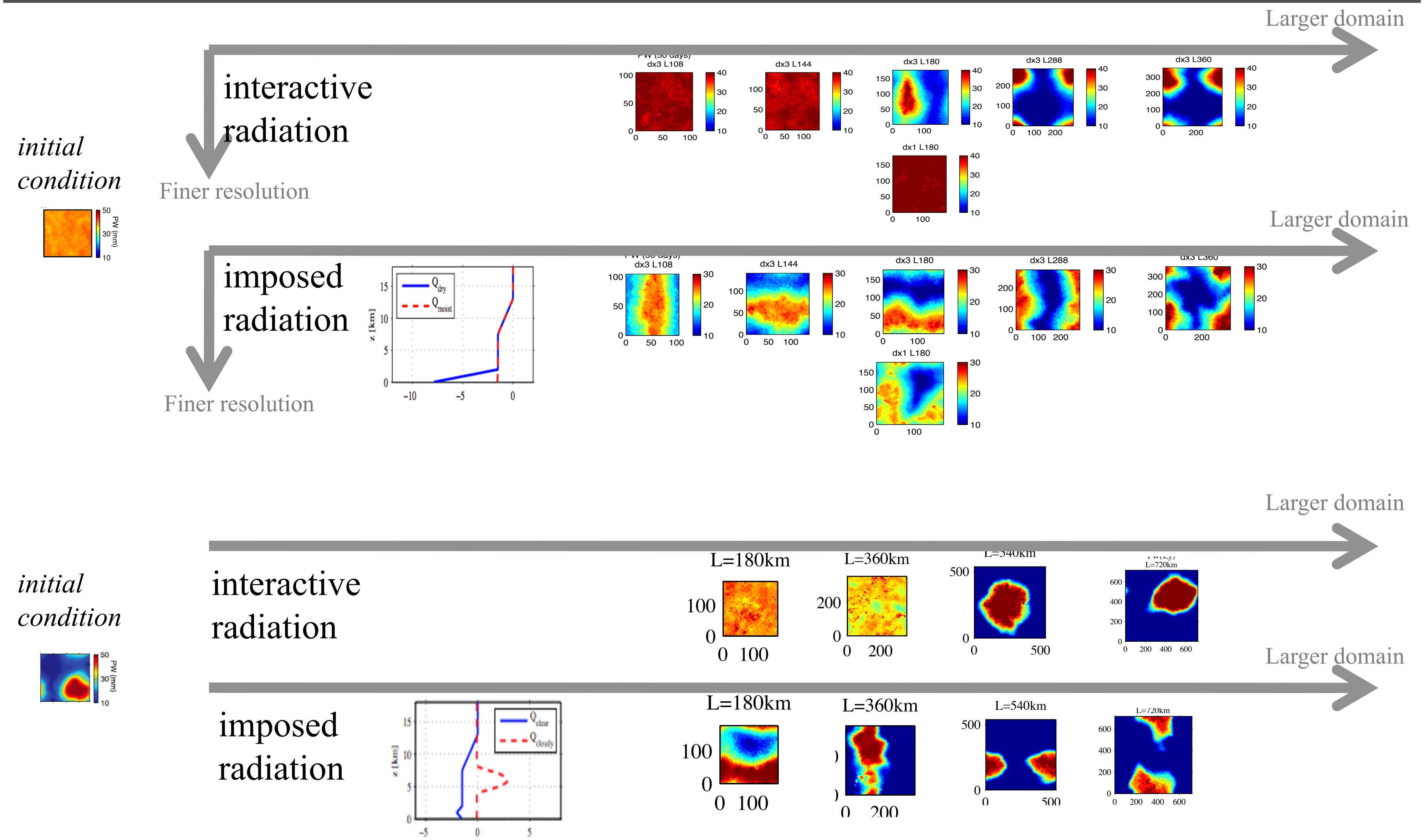


Imposed radiation



⇒ low level cooling in clear region + mid level warming in cloudy region maintain aggregation

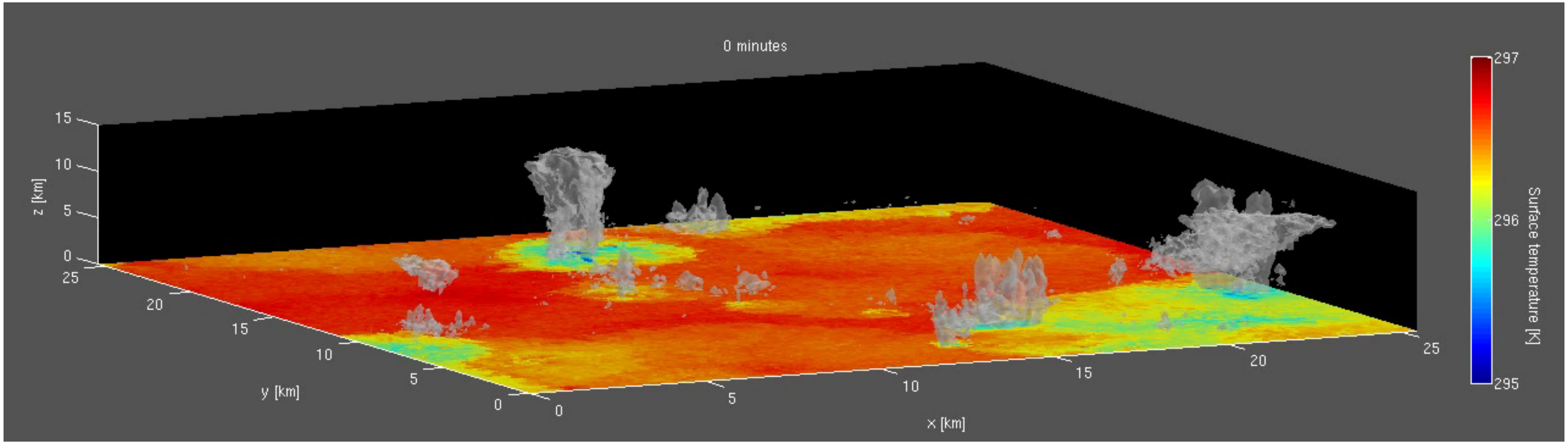
Self-Aggregation: domain size / resolution



⇒ Domain size & resolution dependence due to variability in radiative cooling between dry and moist regions (more low clouds at coarse resolution *[Khairoutdinov et al, JAMES 09]* more variability on large domains)

Self-Aggregation: cold pools

Clouds over near-surface temperature



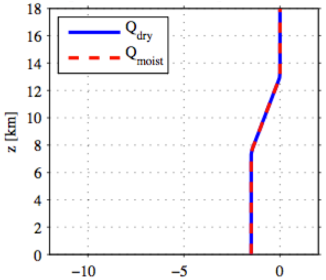
Evaporation-driven cold pools below clouds

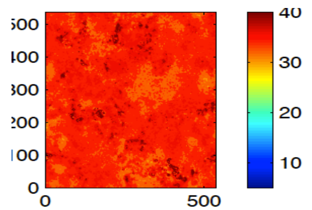
[Jeevanjee&Romps 2013 GRL]

Let's remove cold pools (turn off evaporation of rain in lowest km)

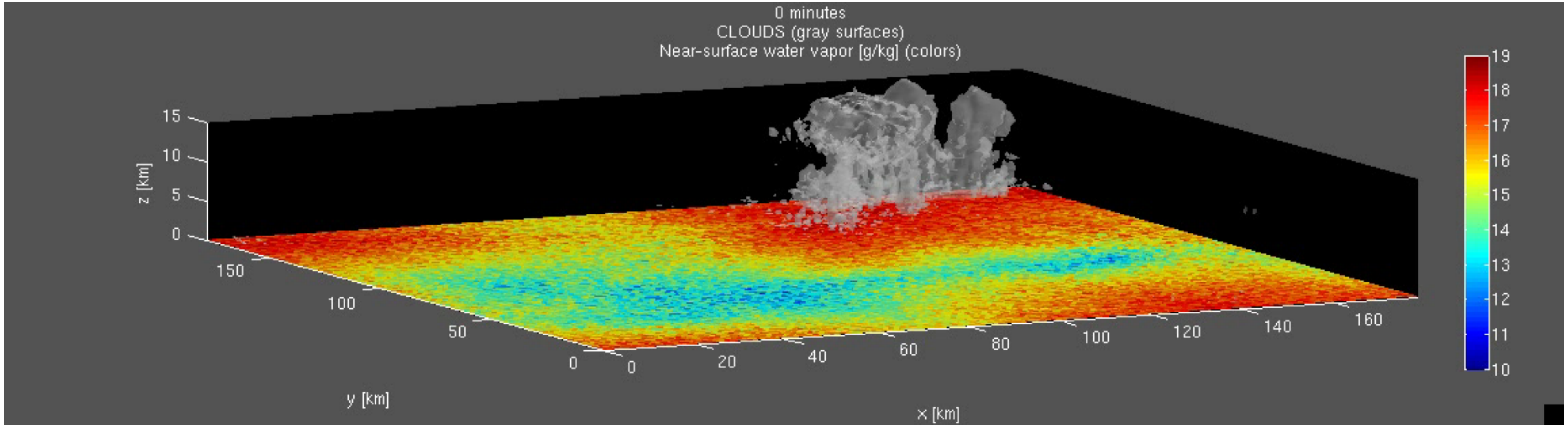
Self-Aggregation: cold pools

Recall:
no self-aggregation with homogeneous radiation





BUT: Simulation without cold pools with homogeneous radiation aggregates



⇒ not same feedback
Water vapor « memory » feedback is responsible for aggregation *[Tompkins JAS 2001, Craig&Mack JGR 2013]*, no downdraft to kill the cloud

Maybe deserves another name « moisture-memory » aggregation

Self-Aggregation

SUMMARY PART 3: SELF-AGGREGATION OF CONVECTION

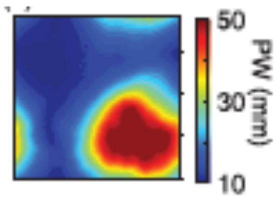
⇒ Variability of radiative cooling between dry and moist regions leads to aggregation
Need either strong low-level cooling in dry region,
or low-level cooling in dry region + mid-level warming in moist region

⇒ « moisture-memory » feedback leads to aggregation
Relevant in humid conditions (i.e. weak cold pools)

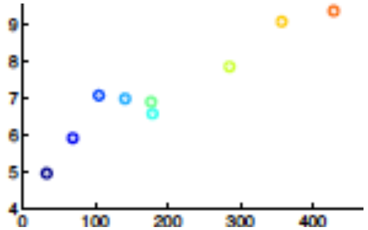
Impact on large scales: towards a parameterization? $agg = fcn(\Delta Qrad, qv_{BL})$
(fcn depends on feedback)

How can CRMs help? Few issues:
- Impact on thermo not clear (drying = cause or consequence?)
- Impact on TOA rad not clear (OLR increase balanced by SW increase?)
- Properties (circulation, size cluster) depend on domain size

R~L/4



max $|u_{BL}|$



L

$$2\pi R\,|u_{BL}| \sim A_{sub}\, w_{sub} \sim L^2 \Rightarrow |u_{BL}| \sim L$$

[Muller, Bony, GRL in prep 2015]

OVERALL CONCLUSIONS

⇒ Clouds are important ingredients of the climate system (radiation, transport…)

⇒ Uncertainties in convective parameterizations propagate through climate models

⇒ Organization still poorly understood and typically not accounted for in parameterizations

⇒ Observations, theory and high-resolution cloud-resolving models useful

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